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THESIS

ENVIRONMENTAL TESTING AND THERMAL ANALYSIS OF THE NPS SOLAR CELL ARRAY TESTER (NPS-SCAT) CUBESAT

by

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June 2011

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This thesis describes the development of a working thermal model of the Naval Postgraduate School's first CubeSat called NPS-SCAT and the accomplishment of environmental testing that has been completed to date in preparation for space launch. The primary mission of NPS-SCAT is to act as a Solar Cell Array Tester (SCAT), providing data on solar cell performance of various solar cells in Low Earth Orbit (LEO). As part of the satellite development process, a detailed test plan was developed and environmental modeling and testing were completed to test SCAT's ability to survive and function in the space environment. A thermal finite element model (FEM) was developed in NX-6 I-deas to analyze and predict the component thermal response to the space environment. Environmental tests, including thermal vacuum (TVAC) and vibration testing, have been completed using profiles determined by the expected launch and on-orbit conditions. The data obtained from these tests validated the thermal model and proved that SCAT would survive the launch conditions and could successfully operate in the space environment.

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This thesis describes the development of a working thermal model of the Naval Postgraduate School's first CubeSat called NPS-SCAT and the accomplishment of environmental testing that has been completed to date in preparation for space launch. The primary mission of NPS-SCAT is to act as a Solar Cell Array Tester (SCAT), providing data on solar cell performance of various solar cells in Low Earth Orbit (LEO). As part of the satellite development process, a detailed test plan was developed and environmental modeling and testing were completed to test SCAT's ability to survive and function in the space environment. A thermal finite element model (FEM) was developed in NX-6 I-deas to analyze and predict the component thermal response to the space environment. Environmental tests, including thermal vacuum (TVAC) and vibration testing, have been completed using profiles determined by the expected launch and on-orbit conditions. The data obtained from these tests validated the thermal model and proved that SCAT would survive the launch conditions and could successfully operate in the space environment.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOP	Argument of Perigee
BCR	Battery Charge Regulator
C&DH	Command and Data Handling
CAD	Computer Aided Design
CDR	Critical Design Review
CFT	Comprehensive Functional Test
CPT	Comprehensive Performance Test
CoM	Center of Mass
COTS	Commercial Off-the-Shelf
CTB	Cargo Transfer Bag
EDU	Engineering Design Unit
EPS	Electrical Power Subsystem
ERD	Experiment Requirements Document
ESD	Electrostatic Discharge
FEM	Finite Element Model
FOV	Field of View
FU	Flight Unit
GC	Generally Clean
GEVS	General Environmental Verification Specification
HTV	H-II Transfer Vehicle
IC	Integrating Contractor
I-deas	Integrated Design and Engineering Analysis Software
ISS	International Space Station
ITJ	Improved Triple Junction
KPP	Key Performance Parameter
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NET	No Earlier Than

NLAS	NanoSat Launch Adapter System
NPS	Naval Postgraduate School
NPSAT1	NPS Spacecraft Architecture and Technology Demonstration Satellite
NPSCuL	NPS CubeSat Launcher
NPS-SCAT	Naval Postgraduate School Solar Cell Array Tester
NRO	National Reconnaissance Office
ORS	Operationally Responsive Space
PCB	Printed Circuit Board
PDG	Payload Developers Guide
PDR	Preliminary Design Review
P-POD	Poly-Picosatellite Orbital Deployer
RAN	Right Ascension of Ascending Node
RBF	Remove Before Flight
RTOS	Real Time Operating System
RTR	Report of Test Results
SC	Spacecraft
SCAT	Solar Cell Array Tester
SIT	System Integration Testing
SITRR	System Integration Testing Review Board
SMS	Solar Cell Measurement System
SpaceX	Space Exploration Technologies Corporation
SRD	SCAT Requirements Document
S/S	Subsystem
SSL	Small Satellite Lab
STP	Space Test Program
TASC	Triangular Advanced Solar Cells
Te	Eclipse Time
TCS	Thermal Control System
Ts	Time in the Sun
TT&C	Telemetry, Tracking & Command

TVAC	Thermal Vacuum
USAF	United States Air Force
USN	United States Navy
UTJ	Ultra Triple Junction

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I. INTRODUCTION

A. THESIS OBJECTIVE

The objective of this thesis is to create a working thermal model of the Naval Postgraduate School's (NPS) first CubeSat called the Solar Cell Array Tester (SCAT) and to develop and conduct environmental testing in preparation for space launch. A derivative of this objective is to develop both a thermal model and an environmental test program that can be customized for future NPS CubeSats.

B. NPS CUBESATS

The goal of the Naval Postgraduate School Solar Cell Array Tester (NPS-SCAT) program is to provide a responsive platform to test solar cells in orbit, while focusing on the education of NPS students and further develop a CubeSat program at NPS [1].

The genesis of NPS-SCAT came after recognizing the educational value that a CubeSat could have for student experimentation and thesis opportunities. The CubeSat form factor is a cube-shaped, stackable spacecraft structure, 10 cm on a side and offers a relatively quick and inexpensive way to develop satellite engineers as well as test small experiments on orbit. Since the launch of PANSAT in 1998, NPS has been developing a technology demonstration satellite, NPSAT1. However, its lengthy design process, construction, and test schedule prevented students from experiencing the complete satellite development process during their tenure at NPS [2].

The idea for the first NPS CubeSat payload came from NPSAT1, which had 10 different payloads. One of these payloads was a solar cell tester. Since many operational satellites have had mission failures or degradations due to the effects of the space environment, there is an ongoing need to demonstrate solar cell performance of varying solar cells prior to using these cells on multi-million dollar satellites. A Solar Cell Array Tester (SCAT) could provide valuable data on solar cell performance in a Low Earth Orbit (LEO) orbit. With the demand for the capability to rapidly test technologies, such as solar cells, and the desire for short cycle satellite development projects for NPS students, the CubeSat provides a responsive and inexpensive solution.

C. ENVIRONMENTAL TESTING

Environmental testing is an important element of the design and testing of a satellite. By conducting tests on the ground, satellite deficiencies can be discovered before launch. This testing process is so crucial because once a satellite is in orbit, it is impossible to make any hardware repairs. Thorough testing will not only uncover poor workmanship but also expose flaws in the design. Proper testing validates the operation of a satellite in the expected space environment long before it leaves the Earth.

Environmental testing for CubeSats is required for two reasons: (1) to ensure that the satellite will survive launch and successfully operate on orbit and (2) to guarantee that spacecraft will not harm the launch vehicle or other satellites within the CubeSat deployer. There are many types of environmental testing including vibration, shock, thermal cycling, and thermal vacuum. While vibration testing was completed on SCAT, this thesis focuses on the most common type of testing: Thermal Vacuum (TVAC) testing.

The thermal vacuum tests were performed in a TVAC chamber which allowed the satellite to be subjected to pressure and temperature changes similar to those of space. A hot soak and cold soak were performed to verify that the materials were suitable for space and ensure the workmanship of the satellite and subsystems was adequate for satellite survivability. These tests are commonly performed at both the subsystem and system level, as needed. Since many of SCAT's components were Commercial Off-the-Shelf (COTS) and previously tested by the manufacturer, the SCAT Test Team conducted only system level thermal testing on SCAT.

D. THERMAL MODEL

Thermal modeling is necessary to predict the satellite's thermal response in the space environment. Modeling can reveal situations when spacecraft component temperature limits will be exceeded, resulting in possible spacecraft degradation or mission failure. If temperature excursions are predicted, modeling can also be used to aid in the design of a thermal control system which can maintain all of a satellite's components within the allowable temperature limits.

A thermal finite element model (FEM) was developed in NX-6 Integrated Design and Engineering Analysis Software (I-deas) to analyze and predict SCAT's component thermal response (NX-6 I-deas is computer aided design (CAD) software used for mechanical design and simulation). The satellite was divided into 21 thermal nodes, each representing a temperature and thermal mass. The material, physical, and thermal properties of each component were entered and the thermal boundary conditions defined. Orbit parameters were input into the program and the simulation was run over several orbits for both a hot case and a cold case. The simulation results illustrated the temperatures that the CubeSat and its components would experience on orbit.

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II. BACKGROUND

A. INTRODUCTION

To ensure satellite survivability during launch and on orbit, every spacecraft program requires detailed and thorough environmental testing. This is also true for the new breed of small satellite known as the CubeSat. To predict the satellite's thermal response in the space environment, thermal modeling is necessary to analyze the component temperatures in the defined orbit. This thesis concentrates on the thermal modeling and testing of NPS-SCAT. As part of the satellite development process, a detailed test plan was developed and environmental modeling and testing were completed to predict SCAT's ability to survive and function in the space environment.

B. SPACE ENVIRONMENT

It is important for satellites to be tested in an environment similar to those in orbit. The space environment is hostile. Satellites experience very low pressures (almost a vacuum), atomic oxygen erosion, orbital debris collisions, and solar radiation. They also face extreme temperature fluctuations as they orbit the Earth, being heated by the sun and cooled during eclipse.

Space is not a perfect vacuum. It contains large numbers of high speed atomic particles (such as nitrogen, molecular oxygen, and atomic oxygen) and energetic photons [3]. Although the density of these particles is very low, their existence means that space has both temperature and pressure that are not zero. The atmosphereic pressure of space is exponentially inversely proportional to altitude. In other words, as our spacecraft goes higher above the earth's surface, the pressure decreases. At 450 km (the expected altitude of SCAT), the atmospheric pressure is approximately 1.5 x 10^{-6} Pascals [4].

In low earth orbit, atomic oxygen is ionized by solar radiation. The chemical process associated with atomic oxygen erosion is a danger for satellites. During its lifetime, a spacecraft will undergo numerous collisions with highly reactive atomic oxygen atoms. These collisions will result in oxidation and erosion of surface materials. A satellite is also exposed to the full spectrum of solar radiation including UV and X rays. Over the lifetime of a satellite in orbit, UV radiation has been known to cause large changes in the absorptivity of certain materials on a spacecraft [3].

The temperature of space is actually difficult to truly qualtify. Temperature is defined as a measure of the relative heat energy of an object and reflects the average kinetic energy of its molecules [5]. Since space is almost a perfect vacuum, it is composed of very little matter and therefore appears to have no real temperature. But space also consists of low energy photon radiating through the universe [6]. While the temperature of this photon radiation can very throughout space, the photons in the thermosphere have a black body temperature of approximately -269˚ C (or almost absolute zero). A thermal vacuum chamber can simulate the pressure and temperature of space, but it cannot imitate the radiation effects and atomic oxygen erosion environment.

C. NPS-SCAT

1. Satellite Overview

The NPS-SCAT satellite is a 1U CubeSat designed to measure, record, store, and transmit data to the ground which can be utilized to evaluate the degradation of the solar cells on orbit over the mission lifetime of the satellite [7] - [8]. SCAT uses a standardized 1U CubeSat Kit Chassis made from anodized aluminum. The base plate and cover plate are customized to allow for the installation of the radio antenna (bottom) and the protrusion of sun sensor (top). The CubeSat bus is composed of mostly Commercial Off-the-Shelf (COTS) components. The bus components are the Microhard MHX 2400 radio, the Clyde Space Electrical Power System (EPS) with Daughter Battery Board, UHF Beacon Board (designed by California Polytechnic State University, hereafter referred to as Cal Poly), and the Pumpkin FM430 Command and Data Handling (C&DH) system. The satellite's primary payload is a Solar Cell Measurement System (SMS) that will capture solar cell performance data in order to characterize the degradation of the cells. Five of the six faces of the CubeSat will house solar cells capable of supplying solar power to the EPS. Figure 1 shows an expanded of view of the satellite components, commonly referred to as the "stack." An expanded view of the integrated stack with solar panels is shown in Figure 2.

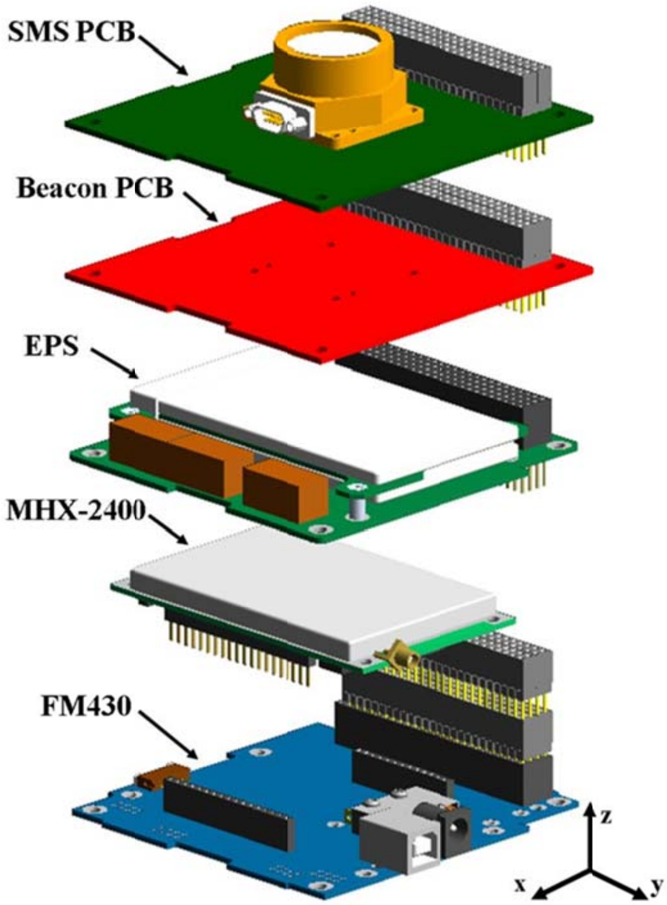

Figure 1 Expanded View of NPS-SCAT Stack (From [7])

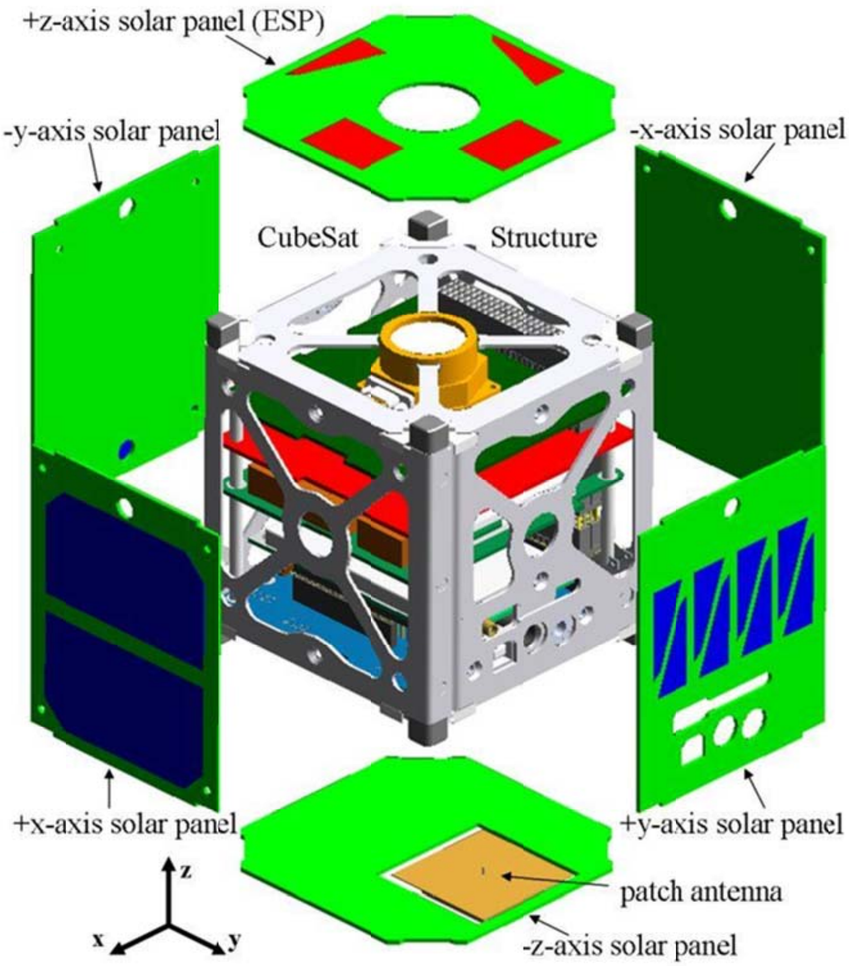

Figure 2 Expanded View of NPS-SCAT (From [7])

The SMS works in conjunction with the sixth face of the satellite, the +Y face, called the Experimental Solar Panel (ESP). The ESP consists of four experimental solar cells, temperature sensors, and a Sinclair Interplanetary SS-411 sun sensor. The four experimental cells are a Spectrolab Improved Triple Junction (ITJ) with cover glass, a Spectrolab Ultra Triple Junction (UTJ) Triangular Advanced Solar Cell (TASC) without cover glass, an Emcore 2nd Generation Triple Junction with Monolithic Diode (BTJM) without cover glass, and a polycrystalline silicon cell without cover glass. The SMS circuit board will capture temperature data and current versus voltage (I-V) curves to characterize the performance of the solar cells and correlate the data with the incident angle of the solar radiation as measured by the sun sensor. The satellite will transmit the information to the NPS ground station for analysis. This combined information will be compared to data generated prior to flight of the vehicle and used to measure degradation of the individual solar cells on orbit during the mission lifetime [8]. Figure 3 shows the integrated satellite and the experimenal solar cells that surround the sun sensor.

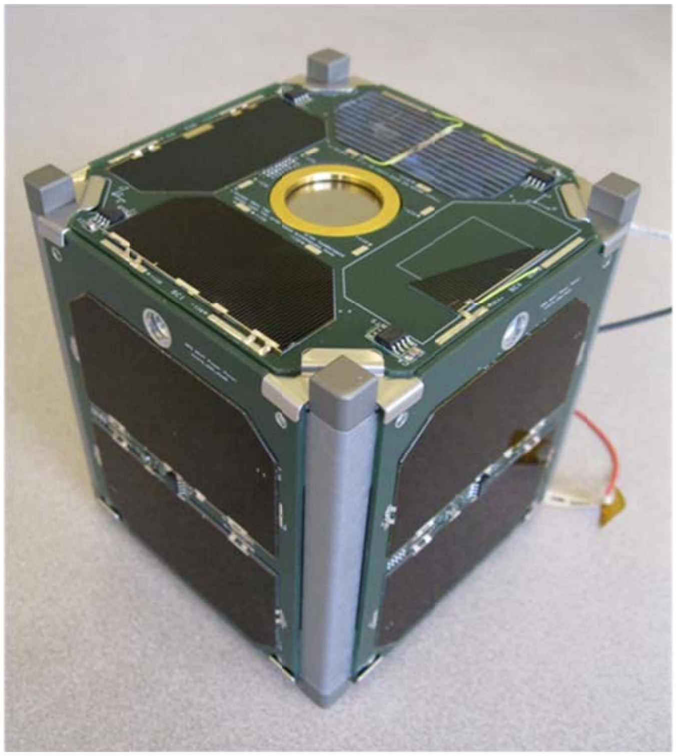

Figure 3 NPS-SCAT

2. Requirements

The requirements for SCAT were written as a set of Key Performance Parameters (KPPs). See Table 1 for a list of the KPPs.

Table 1 SCAT Key Performance Parameters

Number	Key Performance Parameters
001	*The satellite development program shall provide NPS students with an education in the satellite design process, integration, testing, and full life cycle of a space flight system.* This KPP ensures the education and training of military and civilian students by giving a level of hands-on work education on top of classroom experience providing a cadre of future space professionals.
002	*The satellite shall utilize a 1U Pumpkin© CubeSat architecture and Commercial Off-the-Shelf (COTS) hardware whenever possible.* The CubeSat architecture and use of COTS hardware provide a quick and inexpensive way to develop a small satellite and test small experiments on orbit and allowing individual components to be swapped out if needed.
003	*The solar measurement system shall be capable of obtaining solar cell I-V data curve to include solar cell current, voltage, temperature and sun angle no less than once per orbit.* This data will be used to evaluate solar cell degradation throughout the lifetime of the satellite.
004	*The satellite shall be able to communicate Telemetry, Tracking and Command (TT&C) and Payload data to the NPS ground station using an S-band radio (primary transmitter) and/or UHF beacon (secondary transmitter).* This requirement will allow the Solar Cell data to be received remotely and analyzed at the convenience of the operator. It also provides redundancy in the communications systems in case of failures.
005	*The satellite shall transmit TT&C and Payload data regularly (aka "in the blind") via the UHF beacon and transmit data when a communications link is established with the ground station via the S-band radio.* This KPP ensures data is transmitted continuously while also allowing the operator to communicate with the satellite as needed.
006	*The satellite shall be capable of being launched via a CubeSat standard compatible deployer (like a P-POD) on an Evolved Expendable Launch Vehicle (EELV).* Traveling on a launch vehicle that carries another primary payload will keep the total cost minimal while providing access to LEO.
007	*The satellite shall operate continuously in orbit upon launch and have a design life of 1 year.* There are no minimum mission duration criteria; the minimum criteria for mission success are defined by a successful launch, collection and transmittal of any amount of data on orbit.
008	*The satellite development program shall establish the CubeSat program at NPS by creating a CubeSat working group, small satellite process and procedure development, and establishing an engineering support structure.* SCAT will be the first CubeSat to be designed, built, integrated, tested and launched by NPS. The development of a CubeSat program will ensure follow-on projects have all the tools, facilities, processes, and support needed for success.

3. Operational Concept

Upon deployment from the CubeSat Launcher, the NPS-SCAT satellite will initiate a 30-minute timer to allow sufficient separation distance between other space vehicles. At the completion of the timer, the Real Time Operating System (RTOS) is initialized and the FM-430 will verify sufficient battery voltage before powering up the satellite.

The satellite will then enter the "Autonomous" mode which allows the MHX-2400 radio and beacon to transmit and receive. Every 10 minutes, the satellite will collect telemetry consisting of I-V curves, temperature data, and sun angles and store it onboard for future download. The Beacon will transmit a "blip" (aka "Hello World" signal) every 30 seconds and a telemetry packet every five minutes. The MHX-2400 radio will occasionally attempt a handshake with the Monterey ground station. When the satellite is overhead Monterey, CA and the handshake is successful, data will be downloaded to the ground station, located on the NPS campus. The battery voltage will be continuously monitored, and if below a certain level, data will not be transmitted.

4. Engineering Layout

SCAT is a standard 1U CubeSat form and has the dimensions of 10 cm x 10 cm x 10 cm. The only protrusion from the CubeSat form factor is the beacon antenna which, after deployment, is approximately 30 cm in length and anchored (at the center point of the antenna) to the +Y face of the satellite. The antenna will be stowed for launch and deployed no earlier than 30 minutes after satellite deployment from the launch vehicle [9].

According to the CubeSat Design Specification, the total mass of a 1U CubeSat shall not exceed 1.33 kg [10]. The current mass estimate for the completed satellite is 0.859 kg. A detailed mass summary is presented in the NPS-SCAT Experiment Requirements Document (ERD) [9]. SCAT uses a Cartesian right-handed coordinate system with the origin at the geometric center of the CubeSat (see Figure 4). The center of mass must be located at the origin (0,0,0) ± 1 cm. The mass moment of inertia for all three axes is approximately 14. kg-cm^2 [7].

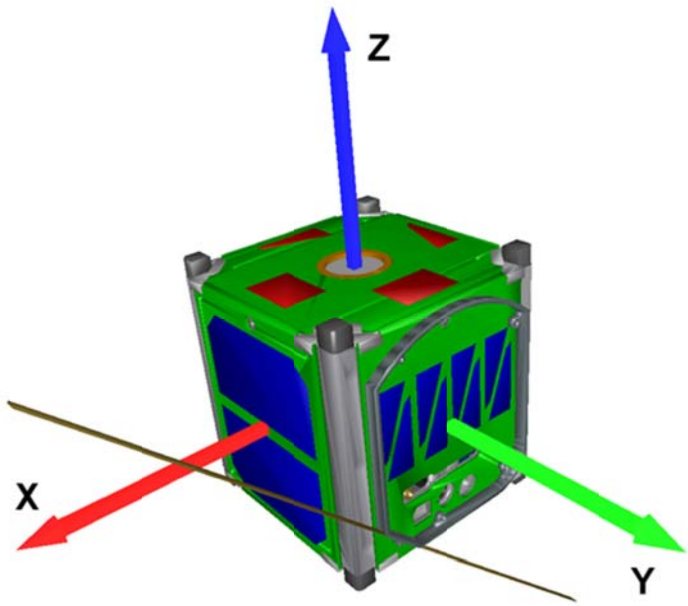

Figure 4 NPS-SCAT Engineering Layout (From [11])

5. Beacon Deployment Mechanism

NPS-SCAT will have only one deployable part, the beacon antenna. Approximately 30 minutes after NPS-SCAT has deployed from the CubeSat deployer the satellite will begin operations. As NPS-SCAT goes through its operational startup phase, a short length of nicrome wire will heat up. The nicrome wire will melt through the piece of fishing wire retaining the antenna and the half-wave dipole antenna will deploy. The half-wave dipole antenna is comprised of two quarter-wavelength radiating elements wrapped around the beacon antenna structure on the top of NPS-SCAT. The antenna will deploy by unwrapping, causing a small exchange of angular momentum with the spacecraft base that is not expected to appreciably affect the rotation of the CubeSat.

6. CubeSat Deployment Interface

While there are several different CubeSat deployers available, the type of deployer used to launch SCAT will depend on the launch vehicle and preference of the integrating contractor. SCAT will most likely be launched from one of the following two deployers: (1) the Poly Picosatellite Orbital Deployer (P-POD) or (2) the NASA Ames NanoSat Launch Adapter System (NLAS) dispenser.

a. *P-POD*

A P-POD is capable of holding three 1U CubeSats, a 1U and a 2U, or one 3U. The P-POD is secured to a launch vehicle (LV), and acts as the interface between the CubeSat and LV. When commanded, the CubeSats are launched using a spring loaded pusher plate. The P-POD, pusher plate and CubeSat structures are shown in Figure 5.

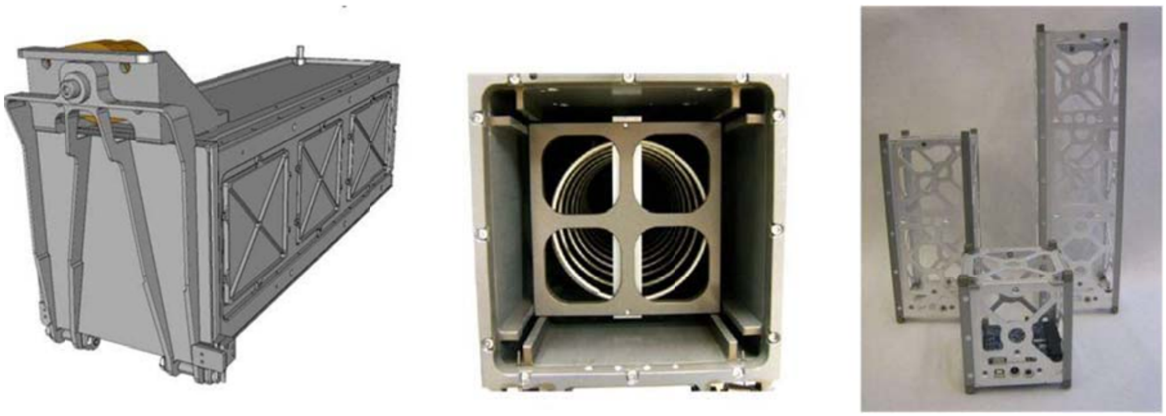

Figure 5 P-POD and CubeSat Structures (2U, 1U, 3U) (From [7])

b. *NLAS*

As of the writing of this thesis, the NLAS is not yet fully functional. Its design is short and cylindrical in shape, commonly called the “wafer” (see Figure 6). The wafer is designed to hold four dispensers that can safely deploy multiple spacecraft per launch (up to 50 kg total mass) and have the flexibility for easy expansion to multiple configurations. The NLAS dispensers will be capable of carrying up to eight 3U CubeSats (or four “six-packs”). Figure 7 and Figure 8 show the NLAS dispenser and how it is mounted in the launch vehicle.

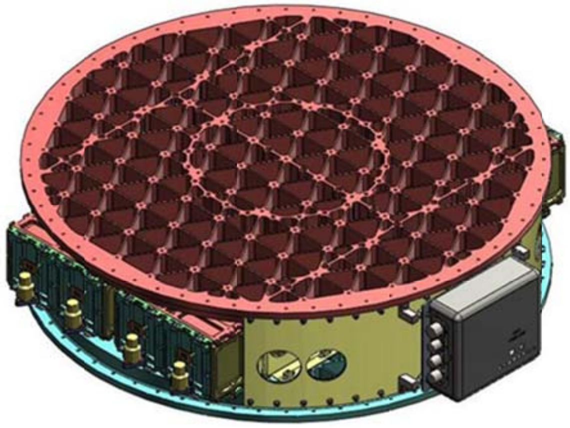

Figure 6 NLAS Wafer (From [12])

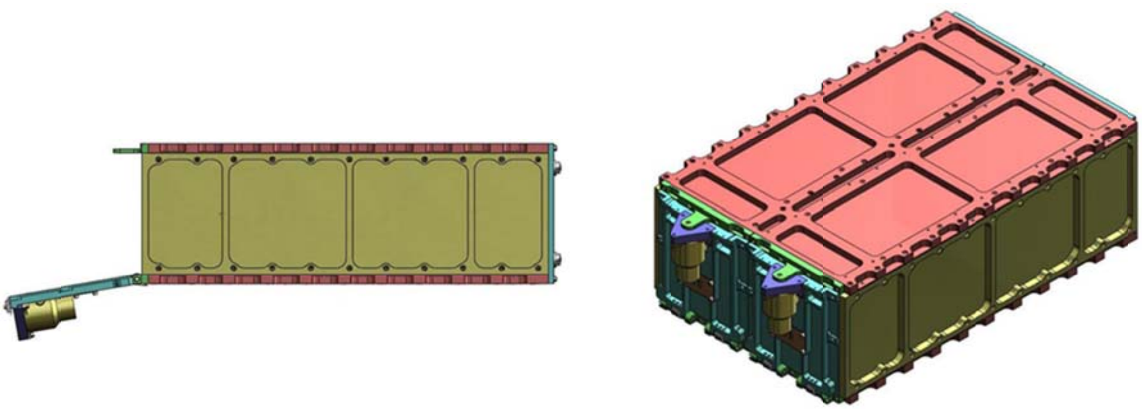

Figure 7 NLAS Dispenser (From [12])

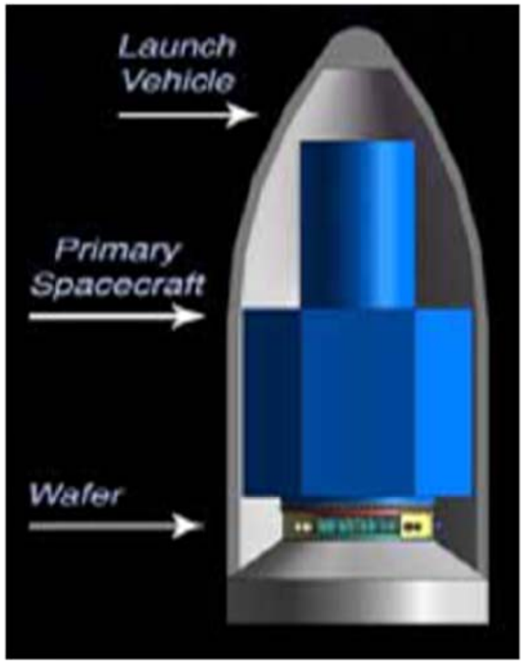

Figure 8 Launch Vehicle—NLAS Wafer Integration (From [12])

D. LAUNCH VEHICLE

a. H-II Rocket to the International Space Station

At the time of this thesis, NPS-SCAT was being considered for deployment by the Japanese via their robotic arm on the International Space Station (ISS) shown in Figure 9. SCAT would receive a "soft ride" in a pressurized Cargo Transfer Bag (CTB) inside an H-II Transfer Vehicle (HTV) [13]. The HTV would launch on an unmanned H-II rocket in the fall of 2011, followed by rendezvous with the ISS. CubeSat deployment would most likely be delayed for several months after launch until a Japanese astronaut could be sent to the ISS. Details about the deployment mechanism and procedure have yet to be determined.

Figure 9 ISS Japanese Manned Space Facility and Robotic Arm (From[14])

b. Falcon 1E

During the initial EDU environmental testing phase, the Space Test Program (STP) was assigned as a secondary payload spot for NPS-SCAT on an NLAS wafer aboard the ORS-1 mission, launching on a Falcon 1E launch vehicle. The Falcon 1E rocket is designed and built by Space Exploration Technologies (SpaceX) of El Segundo, CA. Although launch was originally scheduled for fall 2011, the launch vehicle procurement process failed and the mission was subsequently cancelled.

E. ORBIT DESCRIPTION

Since SCAT is a secondary payload, the orbit in which it will be deployed is dependant upon the primary payload's target orbit. If deployed from the ISS, SCAT's orbit will be similar to that of the station with the following orbital parameters [15].

Table 2 ISS Orbital Parameters

Orbital Parameter	Value
Altitude	~350 km
Inclination	51.6°
Eccentricity	0.0004348
RAAN	15.17°
AOP	356.4°

Note: (1) ISS Orbital Parameters defined on 25 February 2011.
(2) RAAN = Right Ascension of Ascending Node
(3) AOP = Argument of Perigee

All of the thermal model orbit simulations and thermal vacuum testing were conducted under the assumption that SCAT would be launched on the ORS-1 mission. If that had occurred, the ORS-1 mission was expected to be deployed into a low earth orbit as described in Table 3.

Table 3 ORS-1 Mission Orbital Parameters

Orbital Parameter	Value
Altitude	~450 km
Inclination	45°
Eccentricity	0
RAAN	TBD
AOP	TBD

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III. THERMAL ENVIRONMENTAL TEST DESCRIPTION

A. TEST OBJECTIVES

The primary objective of the test program was to evaluate the SCAT satellite for suitability and survivability in the space environment. System level tests followed the standards set out in MIL-STD-1540 [16] and the General Environmental Verification Specification (GEVS) [17] for the Engineering Design Unit (EDU) qualification. This will be followed by acceptance level testing on the Flight Unit (FU). Environmental testing consisted of a thermal vacuum test. The TVAC testing results were used to validate that SCAT would survive launch conditions and successfully operate in the severe environment of Low Earth Orbit (LEO). Technical and operational characteristics demonstrated include the following:

- Functional verification of the payload, communications, and electrical power subsystems before, during and after environmental testing
- Validation of the fully integrated SCAT capabilities and KPPs as described by the SCAT Requirements Document (SRD) [18].
- The secondary objective was to validate that NPS-SCAT can safely be launched in the launch vehicle without damaging other satellite payloads. To ensure the safety of other payloads, specific testing requirements would be defined by the launch provider and must be successfully completed prior to launch vehicle integration.

The tertiary objective of this test program was to educate students in the development of a satellite test program. This supplements the education of military and civilian students by providing hands-on education in addition to classroom experience. The development of a CubeSat test program will ensure follow-on student projects have all the tools, facilities, processes, and support needed for success.

B. SCOPE OF TEST

1. Spacecraft System Testing

This test program was limited to system level environmental testing, encompassing the qualification of the EDU (completed for this thesis) and the acceptance level testing of the Flight Unit (to be accomplished prior to space launch). The thermal environmental test completed was a thermal-vacuum test. Additionally, NPS-SCAT functional and performance testing was done in series with the environmental testing. Table 4 describes the configurations used during NPS-SCAT testing and Table 5 shows the tests that were completed. For a detailed test event listing, refer to the SCAT Test Matrix, Appendix A.

Table 4 NPS-SCAT Test Configurations

Configuration	Description	Name
Engineering Design Unit	EDU with Sun Sensor	EDU
Flight Unit	Flight hardware, clean room only	FU

Table 5 NPS-SCAT Test Descriptions

Test	Description	Test Levels	
		EDU	Flight Unit
Thermal Vacuum (TVAC)	Validate satellite workmanship and simulate on-orbit conditions	Prove survivability at higher/lower than expected temperatures and represent a workmanship verification of the EDU	Acceptance level test based on predicted on-orbit temperatures
Comprehensive Functional Test (CFT)	A CFT took place before and after all environmental tests. This test only included basic satellite capabilities and subsystems that are expected to be susceptible to the space environmental (eg. batteries, solar cell Kapton tape)		
Comprehensive Performance Test (CPT)	A CPT was completed after EDU and Flight Unit testing when it was necessary to validate requirements as dictated by the spacecraft CONOPS. This test demonstrated on-orbit functionality of the satellite in response to commands, EMI, and the space environment (eg. solar cell-to-battery charging and sun sensor I-V curve data)		

2. Test Criteria

a. Subsystem Testing (ST)

Prior to environmental testing, NPS-SCAT subsystems were quantitatively tested to performance metrics specified in the SCAT Requirements Document [18]. Additionally, acceptance testing criteria was met for all flight hardware. All subsystem test points were closed by each subsystem engineer and approved by the NPS-SCAT test engineers prior to the Test Readiness Review (TRR) and subsequent entry into full scale environmental testing.

b. Spacecraft Testing

After system integration and prior to all environmental tests, a CFT was conducted to validate the operation of the satellite. Upon completion of TVAC, another

CFT was conducted to verify that the satellite was still operational. An environmental test was considered successful only if comparable CFT results were reported pre and post-test. Upon completion of EDU environmental testing, a full CPT was conducted for validation of mission requirements.

c. Environmental Testing

Upon completion of spacecraft integration, performance and/or functionality testing, and a TRR, NPS-SCAT underwent full system environmental testing with the ultimate goal of certifying the readiness of NPS-SCAT for LV integration and launch conditions to ensure successful on-orbit operations. It was quantitatively tested to the performance specifications delineated in GEVS and then qualitatively evaluated against the KPPs specified in the SCAT Requirements Document. A detailed summary of test results are described in Chapter IV—Thermal Vacuum Test Results.

3. Test Requirements

All SCAT tests were conducted within limitations as defined by the following environmental test documents:

- MIL-STD-1540, Test Requirements for Launch, Upper-Stage, and Space Vehicles [16]
- General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects - GSFC-STD-7000, April 2005 [17]
- Falcon 1 Launch Vehicle Payload User’s Guide. Rev. 7, 2008 [19]

The test level requirements are typically set by the launch vehicle and communicated and verified by the Integrating Contractor (IC). Since neither the launch vehicle nor the IC were assigned at the time of testing, the NPS-SCAT Team defined the thermal test levels as GEVS or MIL-STD-1540 levels, whichever was higher (or worst case). Since the Falcon 1E launch environment was not published at the time, all thermal vacuum test limits were based on the maximum and minimum predicted temperatures of the orbit environment.

4. Thermal Vacuum Test Levels

a. EDU Qualification Testing

Since there was a dedicated SCAT Engineering Design Unit, the decision was made to test the EDU to qualification levels. This would permit the Flight Unit to be tested to the milder acceptance levels. Of the two documents (NASA GEVS and MIL-STD-1540E), the GEVS thermal vacuum system test levels were the more restrictive. As can be seen in Figure 10, the qualification levels were defined as the maximum expected flight temperature range +/- 10° C. The expected flight temperature range is described in Section 4.c of this chapter. The maximum and minimum test temperatures were defined as +38° C and -42° C, respectively.

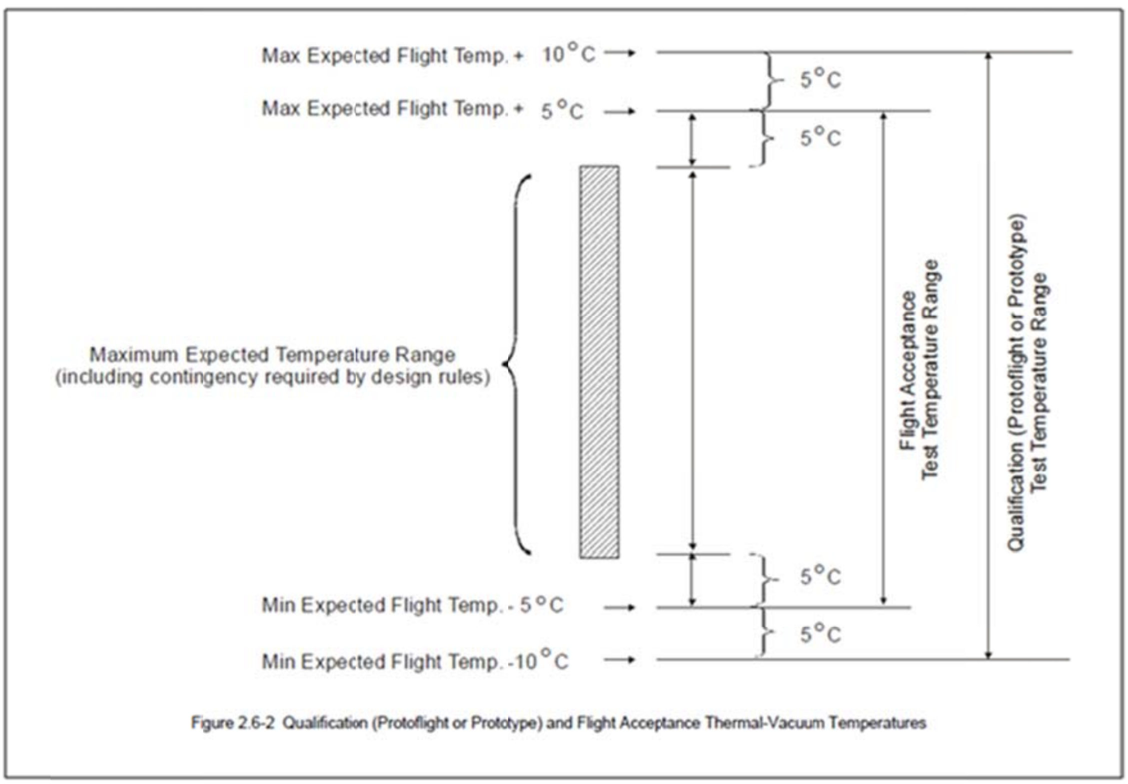

Figure 10 GEVS Qualification and Flight Acceptance TVAC Temperatures (From [17])

The thermal testing profile consisted of a one hour “hot soak”, followed by a one hour “cold soak.” The soaking time was determined by the maximum expected time in the sun or eclipse on orbit. At the time the thermal vacuum testing was completed, SCAT was expected to launch into a circular orbit with altitude of 450 kilometers, an inclination of 45 degrees and an orbital period of 93.58 minutes. This equates to maximum eclipse time (Te) of 37.14 minutes when beta angle = 0˚, and a maximum time in the sun (Ts) of 77.9 minutes when beta = 68.4˚. A cold soak of no less than 40 minutes and a hot soak of no more than 80 minutes were targeted. The TVAC chamber does not imitate a real earth orbit that goes immediately in and out of the sun each orbit. The chamber takes time to heat up and cool down. Since it would take the chamber approximately 30 minutes to heat up and another 30 minutes to cool down to ambient temperature, a hot soak of one hour was determined to be sufficient. The thermal testing profile is depicted in Table 6 and Figure 11 .

Table 6 SCAT EDU Thermal Testing Profile

Time (min)	SCAT Workmanship EDU Test(˚ C)
0	20
36	38
96	38
256	-42
316	-42
444	22

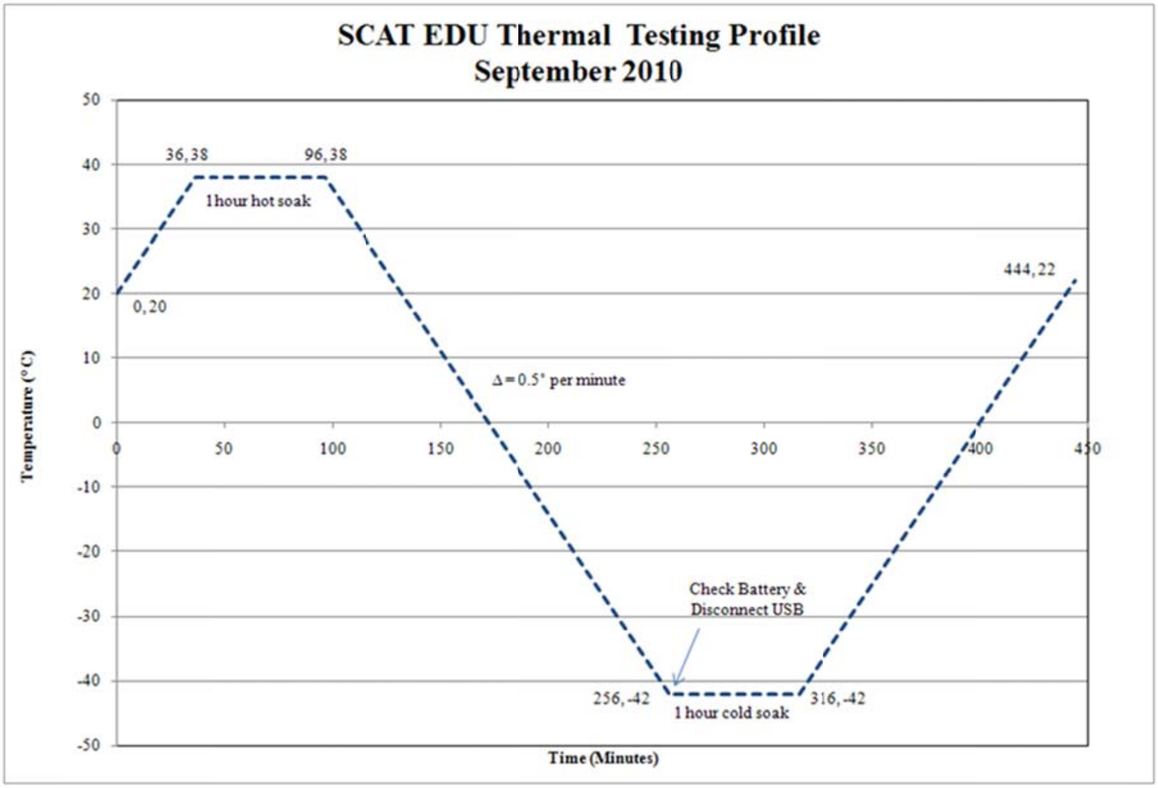

Figure 11 SCAT EDU Thermal Testing Profile

b. Flight Unit Acceptance Testing

Similar to the EDU, GEVS testing levels were used to determine the Flight Unit acceptance tests. As can be seen in Figure 10, the acceptance levels were defined as the maximum expected flight temperature range +/- 5° C. The maximum and minimum test temperatures were defined as +33° C and -37° C, respectively.

c. Maximum Expected Flight Temperature Range

The maximum expected flight temperature range was determined from the predicted on-orbit temperatures. At the time of testing, launch vehicle predicted temperatures were not available. The temperature range was based on the single node thermal model completed by LT Rod Jenkins [7] and verified by Cal Poly SLO on-orbit data of their CP-6 CubeSat which was in a similar orbit to that expected for SCAT [20]. The single node thermal model predicted SCAT would see temperatures from +56° C to -15° C. CP-6 temperature data of the external solar panels showed that their satellite experienced temperatures from +23° C to -27° C. To determine the thermal testing temperature range, a +/- 5° C margin was added to the CP-6 flight temperatures. Therefore, the maximum and minimum predicted temperatures were defined as +28° C and -32° C, respectively. The SCAT thermal testing temperature ranges are shown in Figure 12.

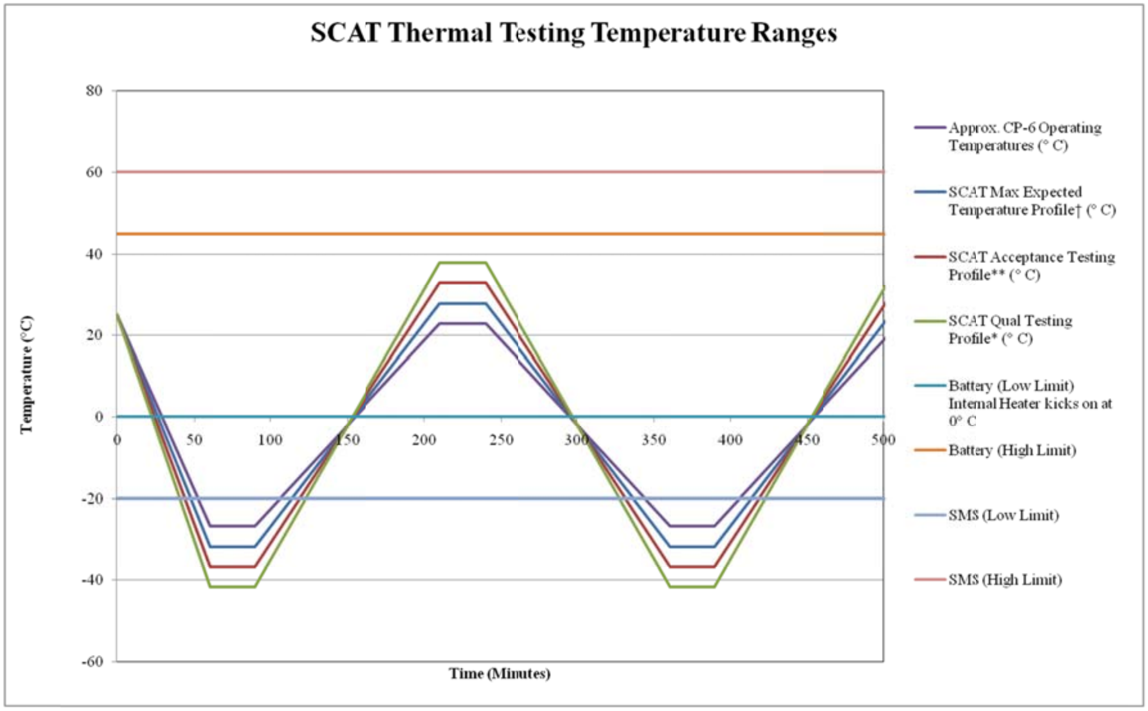

Figure 12 SCAT Thermal Testing Temperature Ranges

5. Integration and Testing Schedule

The following schedule shows the sequence of testing events that were completed (or will be completed) prior to delivery to the Integrating Contractor.

Table 7 NPS-SCAT Test Schedule

Description of Test	Date
Engineering Design Unit Subsystems	
Subsystem Functional Tests	Jan 2010 - June 2010
Subsystem Vibration Test: SMS	July 2010
Engineering Design Unit	
EDU Integration	August 2010
EDU CFT	August 2010
EDU Vibration Test	August 2010
EDU CFT	August 2010
EDU Thermal Vacuum Test	September 2010
EDU CPT	February 2011
Flight Unit Subsystems	
Subsystem Component Bakeout	December 2010
Subsystem Population of Board & Functional Tests	January 2011
Subsystem PCB Bakeout	February 2011
Subsystem Functional Test	February 2011
Subsystem Conformal Coat	March 2011
Subsystem PCB Bakeout (if required)	TBD
Subsystem Functional Test	TBD
Flight Unit	
Flight Unit Integration	TBD
Flight Unit CFT	TBD
Flight Unit Vibration Test	TBD
Flight Unit CFT	TBD
Flight Unit Thermal-Vacuum Test	TBD
Flight Unit CPT	TBD

During NPS-SCAT development and testing, subsystem and system requirements traceability was achieved via the SCAT weekly meeting and the SCAT Requirements Document. Traditional milestones for SCAT development include:

- Preliminary Design Review (PDR)—Completed March 2009
- Critical Design Review (CDR)—Completed May 2009
- EDU Test Readiness Reviews (TRR)—Completed August 2010
- EDU Report of Test Results (RTR)—Completed September 2010
- Flight Unit Test Readiness Reviews (TRR)—Spring 2011
- Flight Unit Report of Test Results (RTR)—TBD
- Pre-Ship Review—TBD
- Post-Ship Review—TBD

6. Limitations to Scope

The following limitations to the NPS-SCAT testing effort should not affect the ability to certify the readiness of NPS-SCAT for LV integration, launch, and on-orbit operations. Subsystem tests were completed by the subsystem engineer and were outside the scope of this test plan. The Flight Unit will not be fully tested in all environments in which it is intended to operate; for example, the Flight Unit will not be subject to the radiation effects and the atomic oxygen erosion environment of space during environmental testing Planned testing environments for the Flight Unit include acceptance level only.

C. THERMAL VACUUM METHOD OF TEST

1. Overview

The primary objective of the thermal vacuum test was to evaluate the SCAT satellite for survivability in the space environment. This was accomplished by simulating on-orbit temperature and pressure conditions and checking for satellite functionality. Test entrance criteria consisted of: (1) subsystem acceptance tests completed, (2) EDU integration completed, and (3) a successful CFT to validate satellite operation prior to thermal vacuum test. Test exit criteria was defined by a successful post-test CFT. A diagram of the test sequence of events is shown in Figure 13.

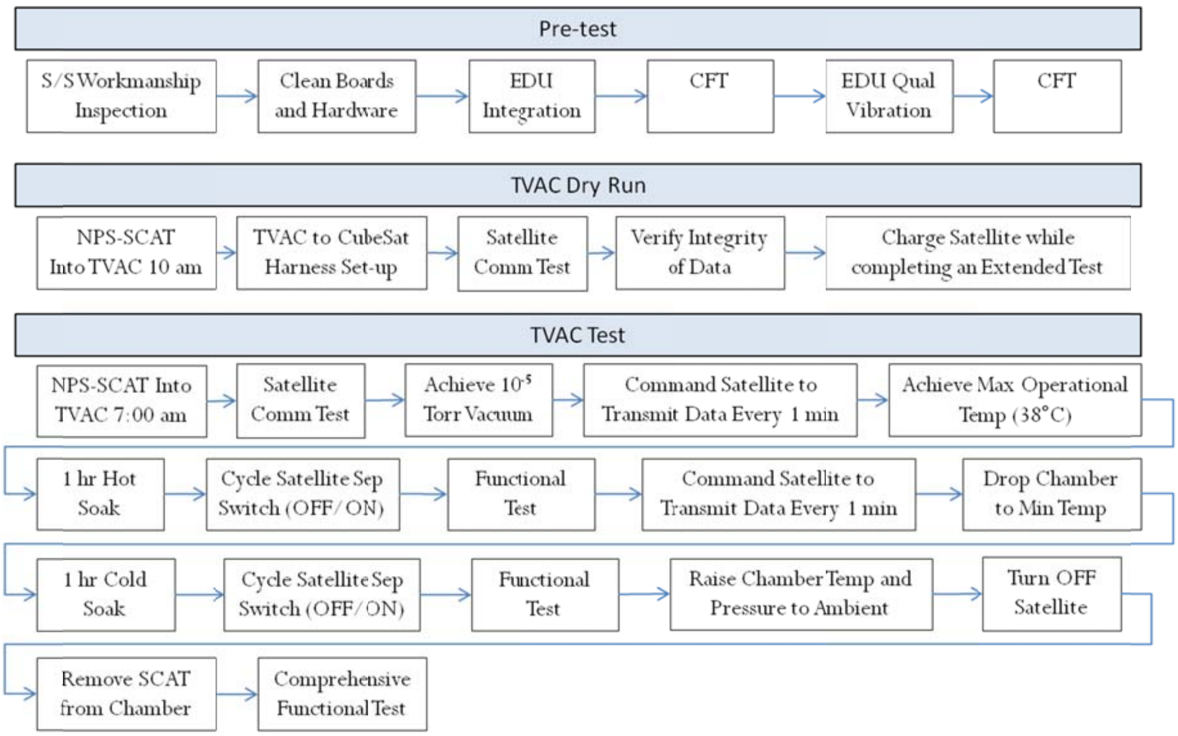

Figure 13 Thermal Vacuum Task Flow Diagram

2. Test Equipment

The TVAC test was completed in the thermal vacuum chamber (Tenney Space Jr.) in the NPS Small Satellite Lab (Figure 14). An Omega HH147 RS-232 Data Logger Thermometer was used to measure temperature data from four thermocouples of which two were placed on opposite chamber walls and two were placed on the satellite (outer surface of +Y and +Z solar panels). The Omega HH147 device was connected to a local lab computer and thermocouple data was recorded on the temperature logging program.

Figure 14 NPS SSL (Tenney Space Jr.) Thermal Vacuum Chamber

3. Test Preparation and Pretest Checks

Test preparation included the determination of the test profile, identifying satellite component temperature limitations, designing a data collection plan, creating a satellite power management strategy for the test, and recognizing safety concerns and/or risks to the satellite. The test profile is discussed in detail in Chapter IV/B.

In order to prevent damage to the EDU, it was important to ensure that no satellite component exceeded its temperature limit during the TVAC test. Each component had a temperature sensor installed and the sensor data was monitored throughout the thermal vacuum test. The temperature limitations of each SCAT component were identified and are listed in Table 8. The components with the most restrictive temperature limitations were the battery, the SMS, and the sun sensor.

Table 8 SCAT Subsystem Operational Temperature Limitations

Node	Description	Tmin(˚C)	Tmax(˚C)
1	Structure +Y side	-65	150
2	Structure Top	-65	150
3	Structure Bottom	-65	150
4	Solar PCB +Z	-40	105
5	Solar PCB -Z	-40	105
6	Solar PCB +Y	-40	105
7	Solar PCB -X	-40	105
8	Solar PCB -Y	-40	105
9	Solar PCB +X	-40	105
10	Patch Antenna	-40	105
11	FM430	-40	85
12	MHX 2400 Radio	-40	105
13	EPS	-40	85
14a	Battery PCB Board	-40	85
14b	Batteries (charging)	0	45
	Batteries (discharging)	-20	60
15	Beacon Board	-40	105
16	Payload (SMS)	-20	60
17	Sun Sensor	-25	70
18	Structure -X side	-65	150
19	Structure -Y side	-65	150
20	Structure +X side	-65	150

Data was collected using two methods. The Omega HH-147 data logger thermocouples transmitted temperature data to a lab computer that operated the Omega 3 thermocouple recording program. These temperature values were monitored in real-time by the test engineers, including the author and Marissa Brummit. Additionally, battery voltage and temperature sensor readings on each satellite component were collected using the MHX 2400 radio to broadcast telemetry from the satellite inside the chamber through a vacuum coaxial cable penetration to a local antenna and thence to a lab computer serving as the ground station. The telemetry data could not be monitored real-time and had to be post-processed after completion of the test.

It was important to ensure that SCAT would be sufficiently powered throughout the test. Because the thermal vacuum test would take about 10 hours, it was determined that the battery life would be a concern. The MHX 2400 radio was the largest power draining component when it was ON and transmitting, requiring 1.2 Watts. To mitigate this issue, the MHX radio was duty cycled to only collect data every 1 minute. Additionally, the satellite could be charged through a USB connection. However, there was concern that charging would introduce extra heat to the test setup that would keep the chamber from reaching the desired cold soak temperatures. The battery and the payload temperature limits restricted the range of testing and the battery minimum temperature limit was more restrictive during charging than during discharging (0˚ C limit for charging and -20˚ C limit for discharging). Therefore, the satellite was only charged during the hot soak, and it was not charged during the cold soak or when the battery temperature was less than 0˚ C.

4. Test Setup

The thermal vacuum chamber setup included cleaning the chamber, placing SCAT inside the chamber, connecting the thermocouples, and preparing the coaxial cables for the radio connection to the antenna. NPS-SCAT was placed on a Delrin test stand that elevated the satellite approximately 4 inches off the bottom of the chamber (see Figure 15). Delrin has a very low thermal conductivity which would ensure that no heat was transferred from the TVAC walls to the satellite via conduction. The stand allowed the satellite to be exposed to the ambient temperature on all 6 sides. The sun sensor was covered with Kapton tape to prevent condensation due to off-gassing.

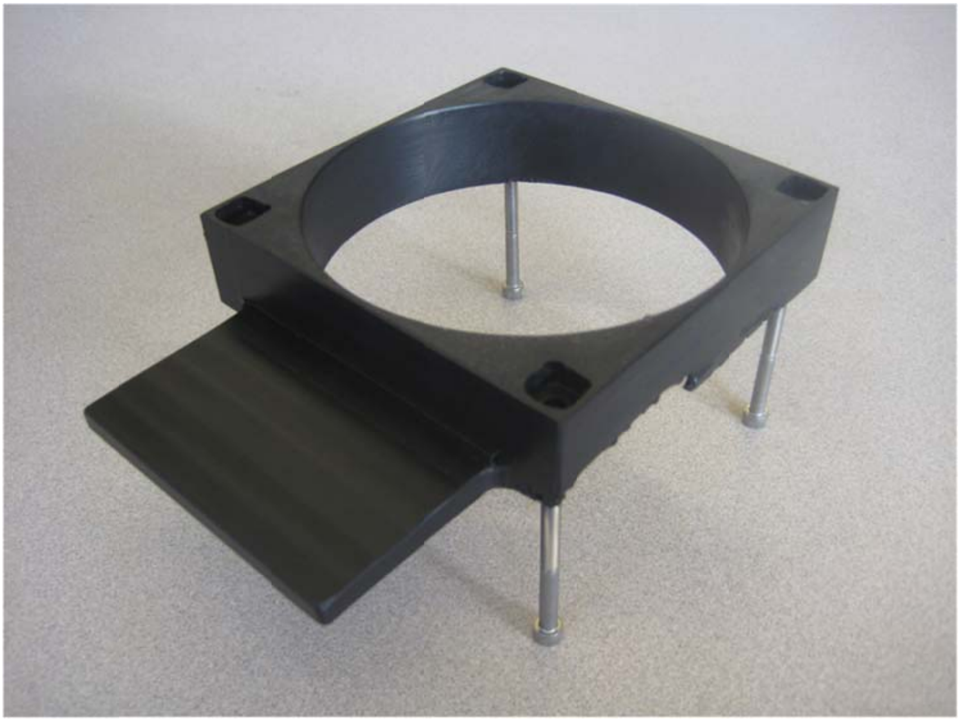

Figure 15 SCAT Delrin Stand

Four thermocouples were available for use; T1 and T3 were placed on opposite chamber walls, and T2 and T4 were placed on the satellite (outer surface of +Y and +Z solar panels). See Figure 16 for thermocouple placement inside the chamber.

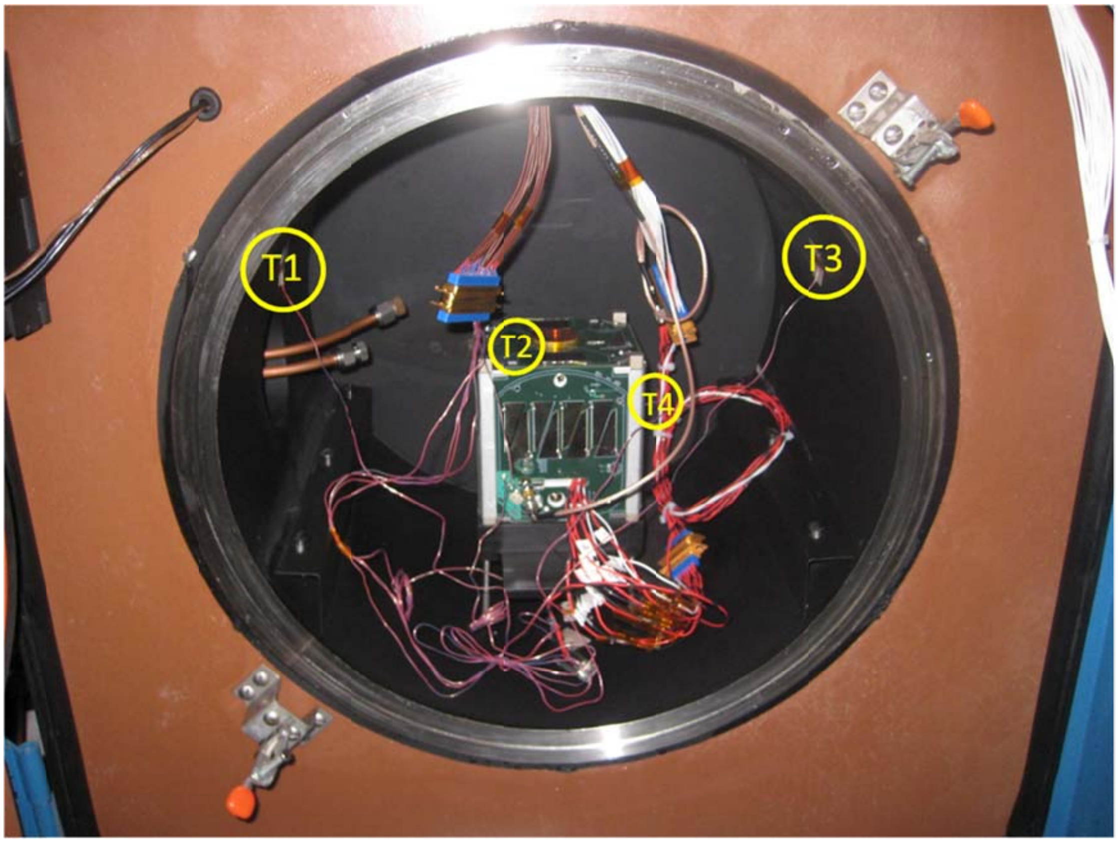

Figure 16 TVAC Thermocouple Placement

Lastly, the test harness and radio coaxial cables were connected. The test harness consisted of a USB power cord and satellite separation switch cables coupled to a DB15 connector. The DB15 connector cable was attached to a DB50 connector which funneled the cables out through the top of the chamber. The output cables were coupled into a USB cable (for charging the satellite) and two separation switch wires. Figure 17 depicts the TVAC connections setup.

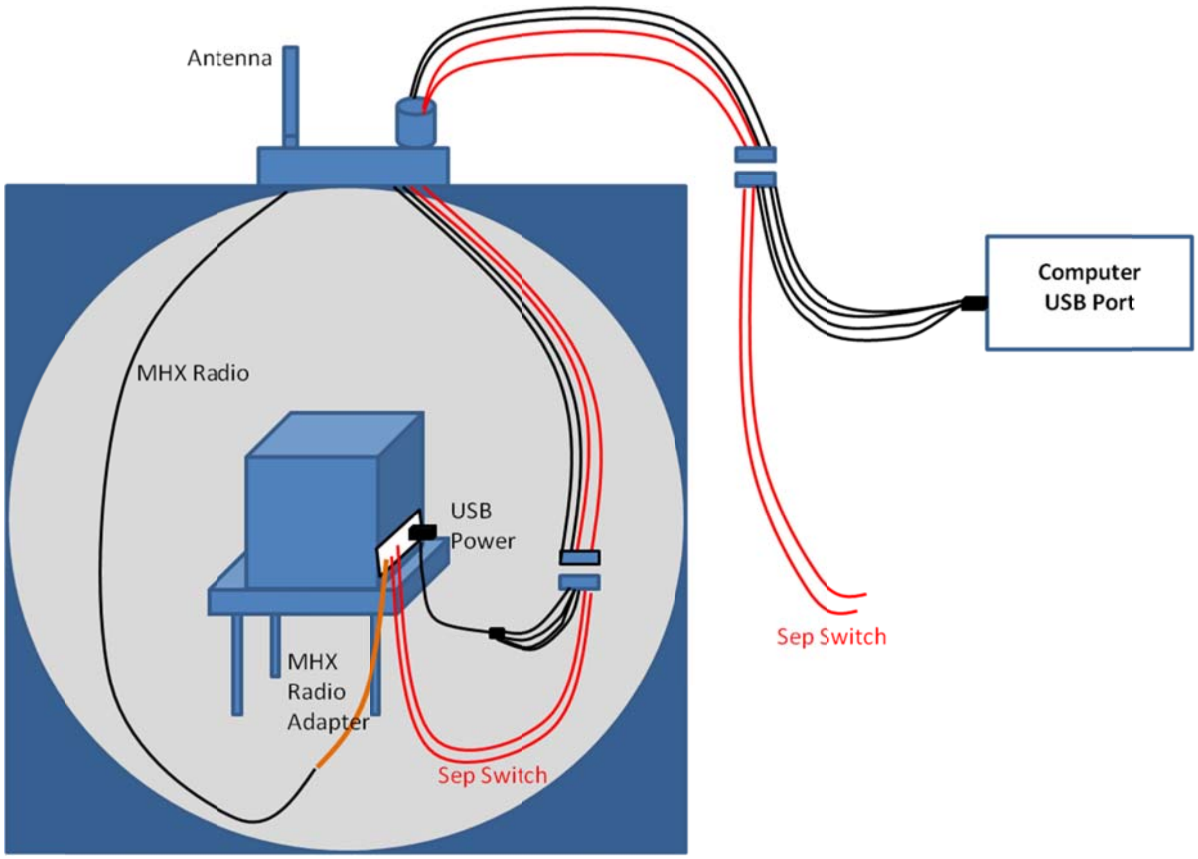

Figure 17 TVAC Connections Set-Up

5. Test Execution

The SCAT EDU thermal vacuum test was conducted on September 2, 2010 from 0700–1730. With the chamber and satellite setup complete, the chamber was closed and powered on. First, the chamber pressure was reduced to 4 x 10^{-5} Torr (5.3 x 10^{-8} atmosphere). Then, the chamber temperature was increased until the average satellite external solar panel temperature was approximately 40˚ C. Since only radiative heating was used, it took approximately one hour to achieve the required hot soak temperature. After one hour of hot soak, the "ambient cooling" was turning ON and the chamber temperature was reduced until the chamber door reached 0˚ C. At that point, the ambient cooling was turned OFF and the sub-zero cooling was turned ON. Again, it took a very long time to cool the chamber since only radiative cooling was available. It took over 3 hours to go from 40˚ C to -33˚ C on the +Y panel. While the objective was to reach an average of -42˚ C on the solar panels, this would have taken an extremely long time if it was achievable at all with the satellite powered ON. The solar panel temperature plateaued at approximately -33˚ C. At this point, it was determined that the TVAC test should continue despite the fact that the targeted temperature of -42˚ C was not attained. A one hour cold soak at -33˚ C was accomplished. At completion of the cold soak, the sub-zero cooling was turned OFF and the heat was turned ON to return the chamber to ambient temperature. Lastly, the chamber mechanical pump was turned OFF, allowing the temperature to return to ambient pressure. Detailed test procedures are presented in Appendix B and the real-time test log is presented in Appendix C.

Four functional tests were conducted on the satellite throughout the TVAC test: (1) inside the chamber before thermal cycle at ambient temperature and pressure; (2) after the one hour hot soak; (3) after the one hour cold soak; and (4) at ambient temperature and pressure after completion of the thermal cycle. The periodic functional tests included sending voltage, current, and temperature data via the MHX 2400 radio to a local lab computer for processing.

6. Test Limitations and Anomalies

There were several test limitations and anomalies that presented themselves during the thermal vacuum test. First of all, the beacon board was still in the development phase at the time of TVAC testing. Therefore, a non-functioning beacon board containing only the antenna deployment circuitry was represented in the TVAC tested EDU. Secondly, it was apparent after the test began that the T3 thermocouple placed on the right wall of the chamber was unreliable. The temperatures presented were unrealistic, if presented at all. Lastly, the chamber was incapable of reaching the cold soak temperature desired of -42˚ C. Based on prior testing and lab technician input, additional liquid nitrogen was thought to be unnecessary to aid the chamber in getting cold. Once discovered, the test was continued but the cold soak was accomplished at -33˚ C instead of -42˚ C.

IV. THERMAL VACUUM TEST RESULTS

A. OVERVIEW

A thermal vacuum test was successfully completed on 2 September 2010 in the Small Satellite Laboratory at NPS. Starting and ending at ambient temperature and pressure, one thermal cycle with a 1 hour hot soak and 1 hour cold soak was completed. The temperature of the chamber was manually operated which accounts for the variation in the temperature profile. Temperature sensors mounted directly on the Battery, SMS, Sun Sensor, and Solar Panel PCBs collected temperature data throughout the test event. The temperature data is presented in Figure 18.

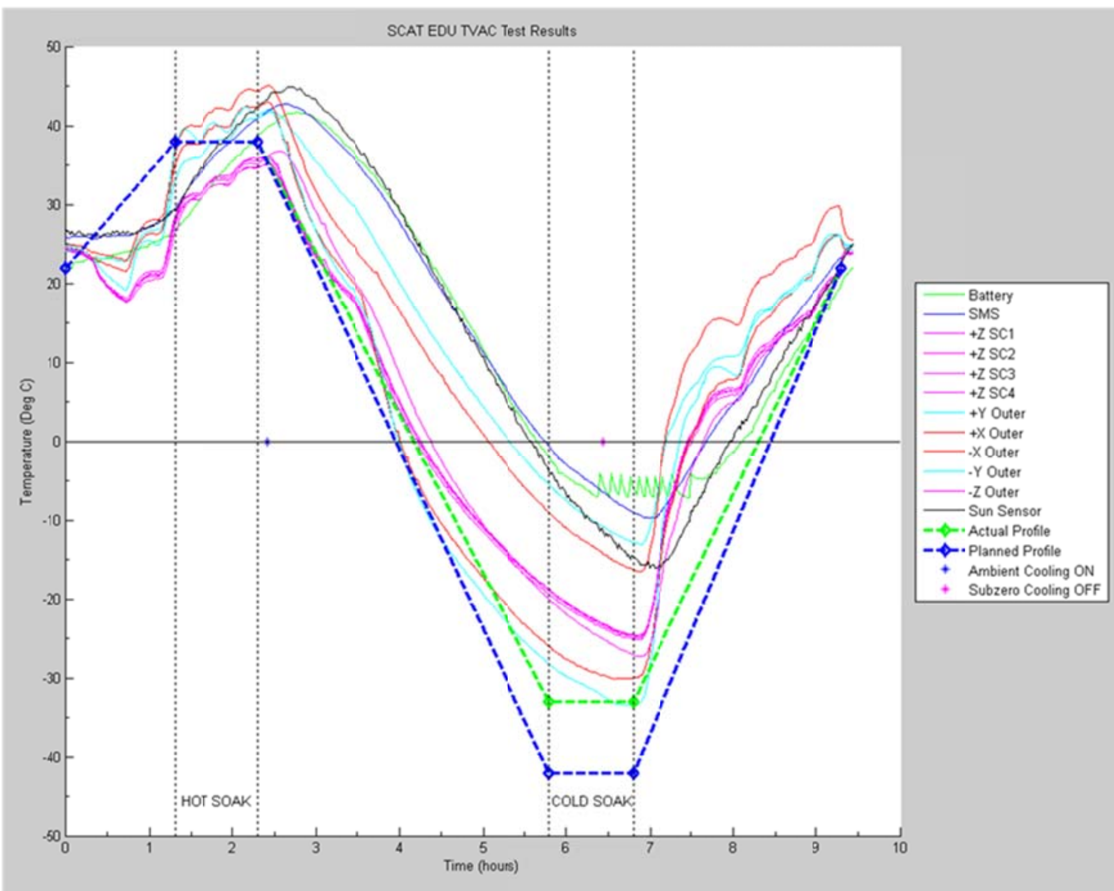

Figure 18 SCAT EDU TVAC Test Results

B. CHAMBER TEMPERATURE PROFILE

As can be seen in Figure 18, the planned profile differed slightly from the actual profile; during the cold soak the solar panel temperature only reached -33˚ C instead of the desired qualification temperature of -42˚ C. When the external solar panels reached approximately -10˚ C, the slope of the temperature time history plot started to shallow because the thermal vacuum chamber did not use liquid nitrogen to keep up with the desired cooling rate. The longer the chamber took to cool down, the longer the satellite was exposed to sub-zero temperature conditions. This resulted in many of the satellite components getting much colder than they would probably get in a 450 km circular orbit.

During the test, a decision was made to complete the cold soak when the coldest external solar panel (-Y) was at -33˚ C because the sun sensor was nearing its minimum temperature limit of -20˚ C. A log of the TVAC test is shown in Appendix C.

C. BATTERY PROFILE

The battery was a critical component for the successful completion of the TVAC test. To ensure that no damage was done to the battery, both voltage and temperature were monitored real-time.

The maximum and minimum voltages of the battery are 8.4V and 6.0V, respectively. Battery discharge below 6V will significantly degrade battery capacity. At 7V, which equates to approximately a 95% Depth Of Discharge (DOD), the battery voltage decreases significantly and rapidly [21]. To avoid damaging the battery, discharging of the battery was not to be conducted below 7V during testing.

The battery was not to be cooled to below its published minimum temperature limits of 0˚ C when charging and -20˚ C when discharging (see [21]). According to the manufacturer (Clyde Space), the battery's internal heater should turn ON at 0˚ C to keep the battery at or above freezing. The battery heater function had not been tested prior to the SCAT EDU TVAC test and was an additional objective of the test.

1. Voltage

To prevent the battery from going below 7V during cold soak, the battery charging cable was left installed for the first half of the test (hot soak) to keep the battery voltage at full capacity (~8.4 V). During the cool-down phase, the battery charging cable was temporarily unplugged but then reconnected when the discharge rate proved faster than expected. Finally, when the battery approached 0˚ C, the cable was unplugged once again and remained unplugged until the battery temperature rose back above 0˚ C. A plot of the battery voltage profile is shown in Figure 19.

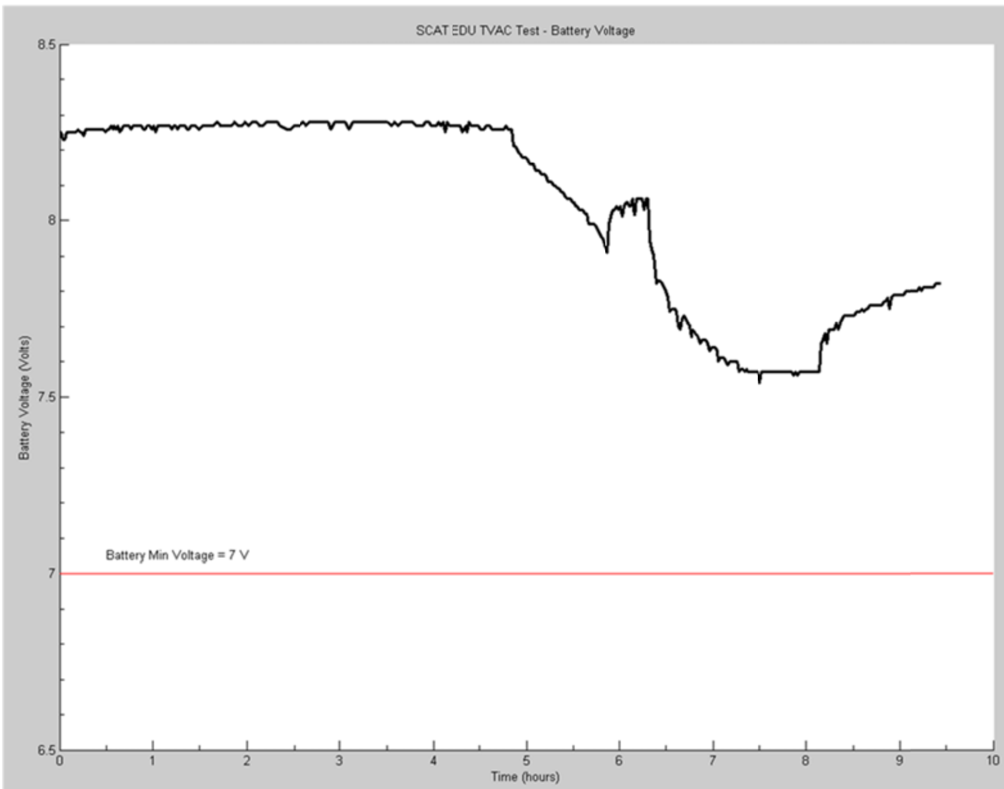

Figure 19 SCAT TVAC Test Results—Battery Voltage

2. Temperature

In order to test the battery heater functionality, the battery temperature was monitored closely as the satellite was cooled below zero. To prevent exceeding the minimum temperature limit of the battery during charging (0˚ C), the charging cable was unplugged prior to the battery reaching 0˚ C. A temperature history of the battery, Figure

20, shows that the battery heater was functional and kept the battery at or above -7˚ C. While the heater did not keep the battery at or above 0˚ C as expected, this was within the manufacturer's battery heater tolerance of ±10˚ C.

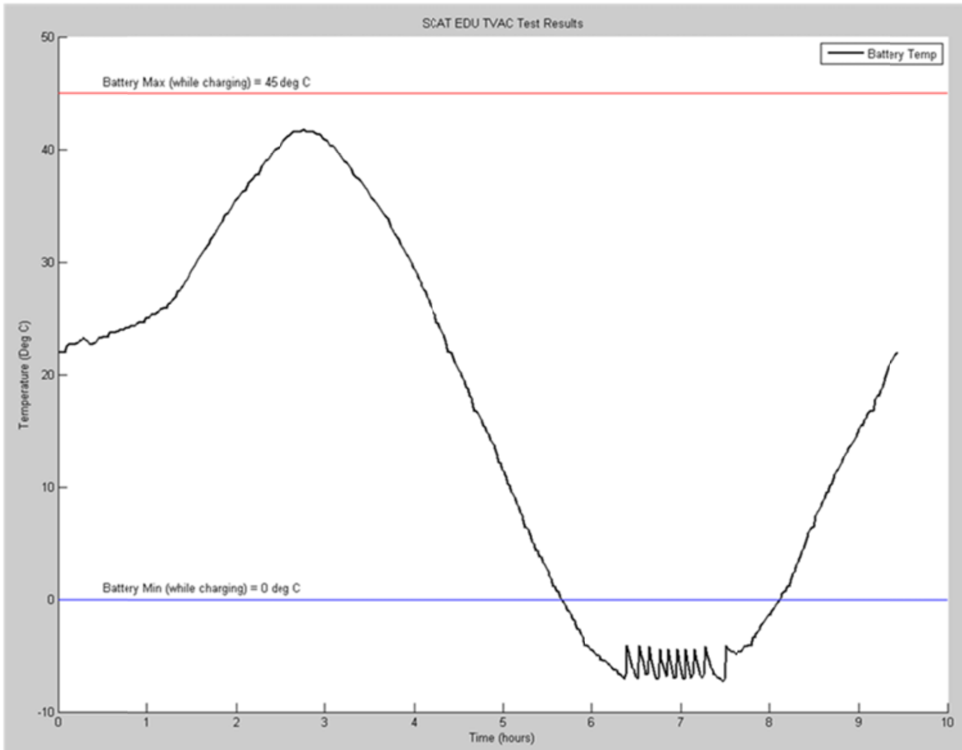

Figure 20 SCAT TVAC Test Results—Battery Temperature

D. COMPONENT TEMPERATURE RESULTS

As planned, no satellite component exceeded its temperature limitations during the TVAC test. Additionally, most of the component's thermal response was as expected. Of note, however, was the difference in the temperature response of the six external solar panels. Considering all six sides of the satellite were made from the same PCB material, with similar solar cells, and experiencing identical exposure to the temperature conditions inside the chamber, it was expected that all the sides would have a similar thermal response. Figure 21 shows the temperature profile of each solar panel.

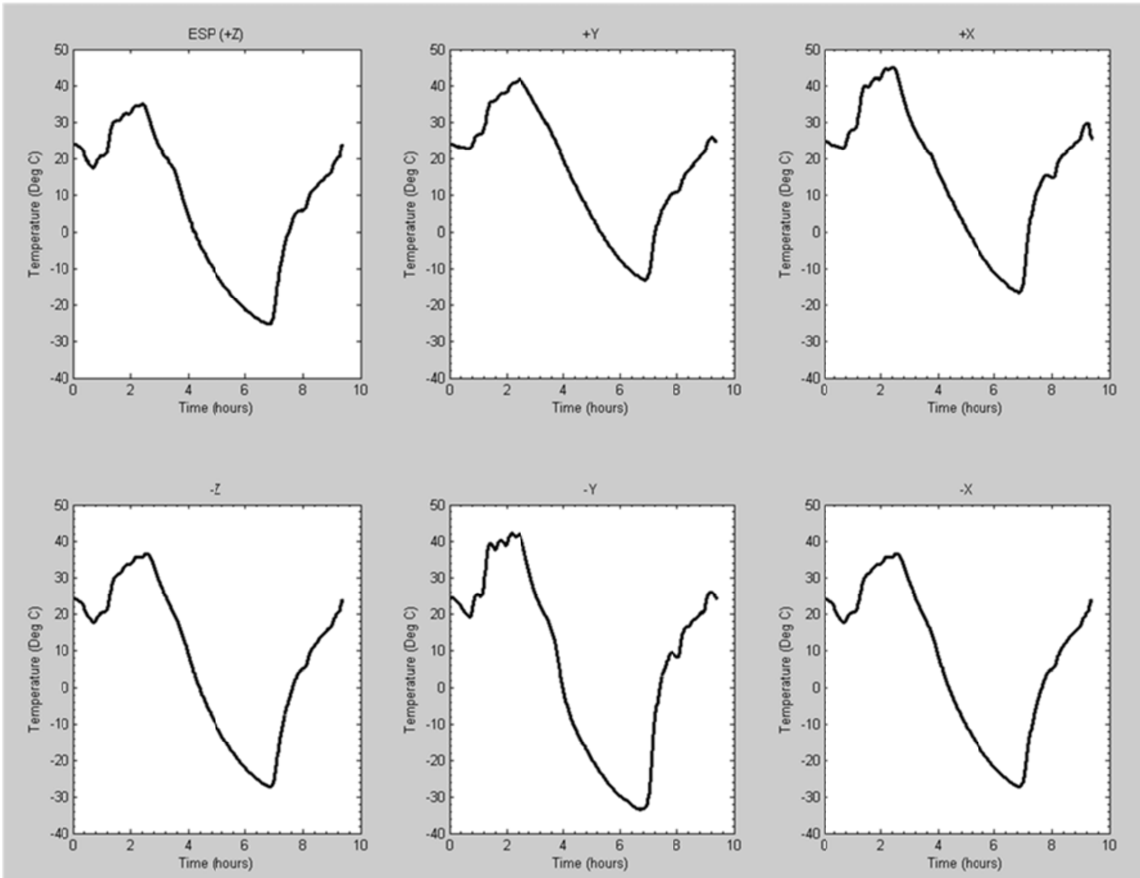

Figure 21 SCAT TVAC Test Results—External Solar Panels

While the +Z and –Z panels experienced similar temperatures, it can be seen from the figure that the +X panel was consistently ~10˚ C warmer than the –X panel throughout the test. Considering these panels are identical, there are two possible reasons for the large difference in temperatures. One reason could be due to the stack of bus connectors that are mounted just inside the –X solar panel. This column of connectors could prevent heat from the internal satellite components from reaching the –X panel. Another reason for the large temperature differential could be due to inconsistencies in the temperature distribution throughout the thermal vacuum chamber.

Additionally, while the +Y and –Y panels showed similar "hot" temperatures, their cold temperatures differed by almost 20˚ C (where the +Y panel was the warmer panel). While one cause of this temperature difference could be due to the slightly different solar panel layouts of each board, it is more likely due to the positioning of the satellite in the thermal vacuum chamber. The hotter +Y panel was facing the “front” of the chamber (the door) and the colder –Y panel was facing the back wall of the chamber. It is probable that the front of the chamber was considerably warmer than the back of the chamber possibly due to the door heat which was used to heat the chamber.

V. THERMAL FINITE ELEMENT MODEL (FEM)

A. THERMAL DESIGN PROCESS

The thermal design process is a multi-step progression combining selection of a thermal design and completing temperature analysis to validate the design. The objective of the process is to select a highly reliable, low cost, simple design for the component or spacecraft. In keeping with this philosophy, the design should be no more complex than required [22]. In the case of many CubeSats, there are few, if any, thermal control devices installed on the components.

The first step of the thermal design process is to understand the objectives and constraints [22]. Other CubeSats, similar to SCAT, were designed with minimal or no thermal control system. After reviewing temperature data from these CubeSats already in orbit, it was evident that an active thermal control system (TCS) would most likely not be necessary. SCAT has a passive TCS that takes advantage of of the built-in coatings of the external materials and components. Thus, the objective for the SCAT thermal design process was not to design a new TCS, but to predict the on orbit temperatures for SCAT in its current configuration and confirm that they were within the allowable temperature limits for each component. SCAT is a free tumbling satellite which should present favorable temperature results since each face will be continually rotating its view factor from the earth, to the sun, and to deep space.

The second step of the process is to select the approach to problem resolution [22]. When determining the approach to take, it is important to consider the schedule, budget and risk. Given the low SCAT testing budget and limitations of the student thesis timeline, the approach selected was to create a thermal model of SCAT to predict the temperatures in our assigned orbit. But just how detailed of a model was needed? Without previous CubeSat experience to reference, three SCAT models were created of increasing complexity in search of the answer to this question. The first thermal model created was a single-node model created by the Systems Engineer, LT Rod Jenkins. While this model predicts an overall temperature range of –15˚ C to +47˚ C, it is unable to provide predicted temperatures for individual components. The details of this simple model are documented in his thesis [7]. The second thermal model was a 20-node model constructed by Major Michele Woodcock, LT David West and CDR Kerry Smith [23].. Unfortunately, this model exposed the difficulties inherent with conducting a complicated multi-node thermal model in Microsoft Excel and Matlab. The model was extremely complicated, the analysis was incomplete and the results were unrealistic due to the limitations of the software. After realizing the shortcomings of using Excel and Matlab, a third model was created using a CAD program (NX-6 I-deas) that had a Thermal Model Generator (TMG) and an orbital simulation mode. This model is described in detail in Section C. Comparison of the single node model and the CAD model is presented in Chapter VI, Section B.

The third step of the thermal design process is to make a detailed schedule and cost estimate [22]. Creation of the thermal model would fall under the responsibility of the Test Engineer. Using an NPS student to complete the work, SCAT's thermal model needed no monetary funding, but would require time to research thermal modeling, learn how to use the NX-6 I-deas program, develop the model and post-process the data. Initially, six weeks was allotted to complete the work. However, the time required was underestimated and it ended up taking over 10 weeks of concerted effort to complete the task.

The fourth step in the thermal design process is to begin design analysis [22]. This is done in two parts: (1) communicate with subsystem engineers to understand the objectives, limitations and requirements of their subsystem and (2) gather data—component size, weight, materials, thermal properties, duty cycles, connections, conops, orbit parameters, and the expected thermal environment from prelaunch through end of life. This proved to be one of most time consuming steps of the entire thermal analysis process. The data collected is shown in Section C.

The fifth step is to construct the thermal model [22]. The engineer must design a thermal math model (TMM) consisting of thermal mass and boundary conditions to predict component temperatures and a geometric math model (GMM) to calculate the view factors and radiation couplings between all the physical surfaces and the environmental fluxes (solar, earth IR and albedo radiation). By using NX-6 I-deas, both the TMM and GMM were created inside the program, which removed the need for a creating a separate view factor matrix. Once completed and debugged, the thermal model was run over several orbits under the worst case hot and cold conditions (including orbit beta angle and component duty cycles).

The final step of the thermal design process is documentation [22]. This includes the thermal design, detailed analysis, predicted temperatures, assumptions and recommendations. In addition to presenting the results of the analytical work, this thesis serves as the documentation for the SCAT thermal analysis.

B. PRINCIPLES OF THERMAL MODELING

1. Thermal Heat Load

a. Environmental Heating

In orbit, spacecraft are subject to numerous types of environmental heating. The main types of environmental heating are direct sunlight (solar), reflected solar energy off the Earth (albedo), and Earth infrared energy [22] (see Figure 22).

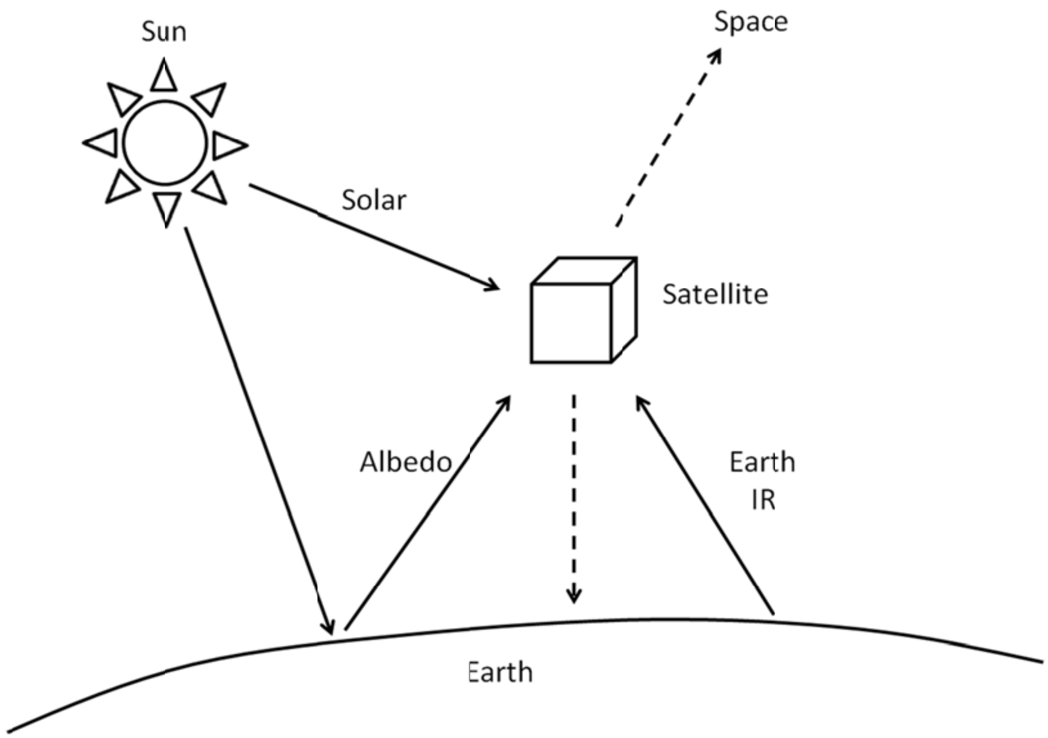

Figure 22 Satellite Thermal Environment

In addition to environmental heating, the spacecraft is affected by the power dissipated by the electronic equipment onboard the satellite (Q_{equip}). The input heat load (Q_{in}) to the spacecraft is defined as the sum of all these factors, shown in Equation 5-1 [24].

$$Q_{in} = Q_{sun} + Q_{earth} + Q_{albedo} + Q_{equip} \tag{5-1}$$

b. Heat Transfer Within the Spacecraft

In any spacecraft, heat will flow from an area of higher temperature to an area of lower temperature. The three modes by which heat flows from one component to another are radiation, conduction and convection. Radiation is the process by which heat flows between two bodies separated in space [22]. It is the primary heat transfer method outside the spacecraft but can be a major concern within large cavities of the satellite. Conduction is the process by which heat flows within a medium or between different mediums in direct physical contact [22]. It is the primary heat transfer method inside the spacecraft and usually overpowers the heat transfer by radiation. Convection is the process of energy transport by combined action of heat conduction, energy storage, and mixing motion [22]. Most satellites will not be affected by convection because it is a function of fluid motion. Some exceptions would be hermetically sealed units and satellite that utilize heat pipes for thermal control.

The total environmental heat load that is subjected upon the spacecraft system (Q_{in}) will be equal to the summation of the stored capacitance ($\mathrm{m}\dot{T}$), internal conduction exchange (CT), internal radiation exchange (RT^4) and the output radiation load (rT^4) as shown in Equation 5-2 [24].

$$Q_{in} = \boldsymbol{m}\dot{T} + \mathcal{C}T + \mathcal{R}T^4 + \boldsymbol{r}T^4 \tag{5-2}$$

The four major inputs to the heat loads are described as follows:

$Q_{ci} = \boldsymbol{m}\dot{T}$ = Stored Capacitance where:

$\boldsymbol{m}$ = Equivalent Mass of the system ($\boldsymbol{m} = c_p m$ where c_p is the specific heat capacitance and m is the nodal mass) and $\dot{T}$ = nodal temperature rate of change

$\mathcal{C}T$ = the Internal Conduction Exchange where:

$\mathcal{C}$ = Conduction Matrix and T is the temperature

$\mathcal{R}T^4$ = the Internal Radiation Exchange where:

$\mathcal{R}$ = Radiation matrix (Internal) and T^4 is the temperature raised the 4th power

$\boldsymbol{r}T^4$ = the Output radiation load where:

$\boldsymbol{r}$ = Radiation matrix (External) to deep space and the Earth and T^4 is the temperature raised the 4th power

2. Thermal Nodes

One of the first steps to developing a thermal model is to divide the spacecraft into finite sub volumes called thermal nodes. A node is represented by an average temperature and a thermal mass. Since a node is a concentration of parameters at a single point, it is ideal to assign nodes to regions of homogenous material or at least materials with consistent thermal properties. It can be said that assignment of nodes is more of an "art than a science." Spacecraft thermal design experience, previously conducted thermal analyses, and required level of detail will drive a thermal engineer's nodal assignments. A thermal model with numerous nodes will be more detailed and (ideally) more accurate than a model of fewer nodes. With that being said, the thermal engineer should choose the minimum number of nodes so that the thermal model is no more complex than required and yet still gives temperature predictions for each of the desired components. Time allotted for thermal design must be taken into consideration when defining nodes. Thermal models with numerous nodes will take significantly more time to create, need specialized software, require a processor with considerable computing power, and may require additional analysis.

C. MODEL DEVELOPMENT

The first step of the thermal model development consisted of assigning the thermal nodes. Once the nodes were defined, NX-6 I-deas was used to build the model parts, meshing the finite element model, entering the material and physical properties of each component, defining the conduction matrix and defining thermal boundary conditions. After construction of the SCAT model was complete, the orbit parameters were defined and the simulation was executed over several orbits. After completion of the TVAC test, the model was run again with the TVAC temperature profile to compare results from the test with the model. The last step was to complete post-processing and data analysis.

1. Defining Thermal Nodes

Since each subsystem had temperature limits that should not be exceeded on orbit, thermal node assignment began by defining each subsystem as a node. Although the

CubeSat structure was one cohesive unit made of the same aluminum, a node was assigned to each side of the cube. This decision was made since each structure wall would have a completely different view factor to deep space, the sun, or the earth than the other sides. For that same reason, each solar PCB was assigned as a separate node. The solar PCBs are considered one node each, since laboratory testing showed the same temperatures on either side of the board. Lastly, the patch antenna and the sun sensor were each defined as a node since their properties were dissimilar to their respective subsystem PCB boards. The nodes used are shown in Table 9 and Figure 23, Figure 24, and Figure 25.

Table 9 SCAT Thermal Analysis Nodes

Node #	Description	Node #	Description
1	Structure +Y side	11	FM430 C&DH
2	Structure Top	12	MHX2400 Radio
3	Structure Bottom	13	EPS
4	Solar PCB +Z	14a	Battery Board
5	Solar PCB -Z	14b	Battery (2 cells)
6	Solar PCB +Y	15	Beacon Board
7	Solar PCB -X	16	Payload (SMS)
8	Solar PCB -Y	17	Sun Sensor
9	Solar PCB +X	18	Structure -X side
10	Patch Antenna	19	Structure -Y side
-	-	20	Structure +X side

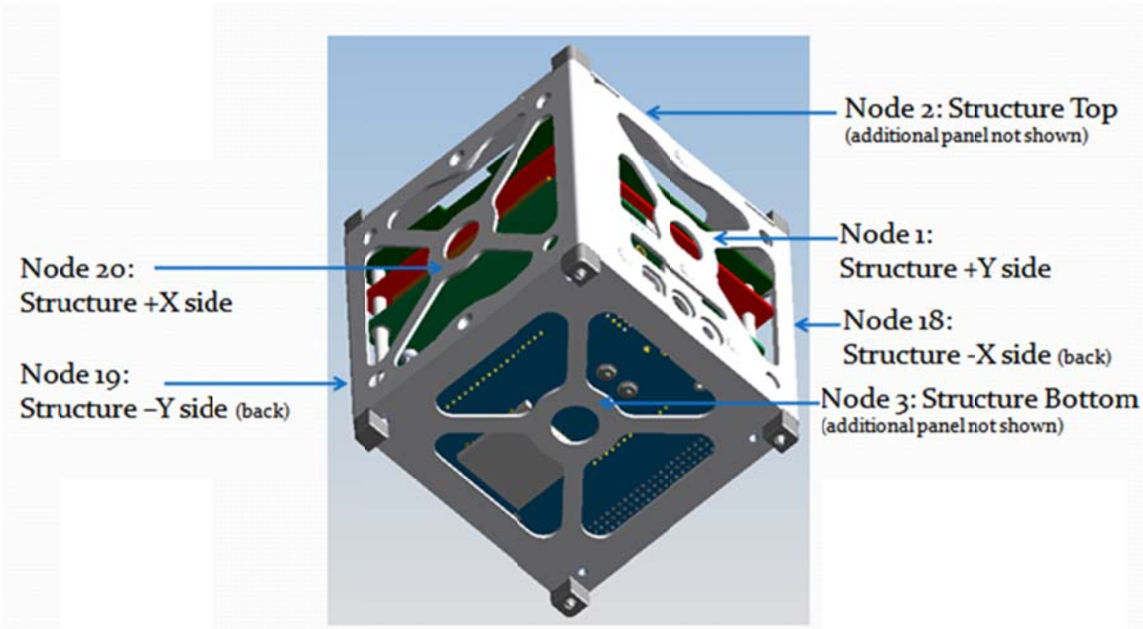

Figure 23 SCAT Thermal Analysis Nodes 1–3, 18–20 (From [23])

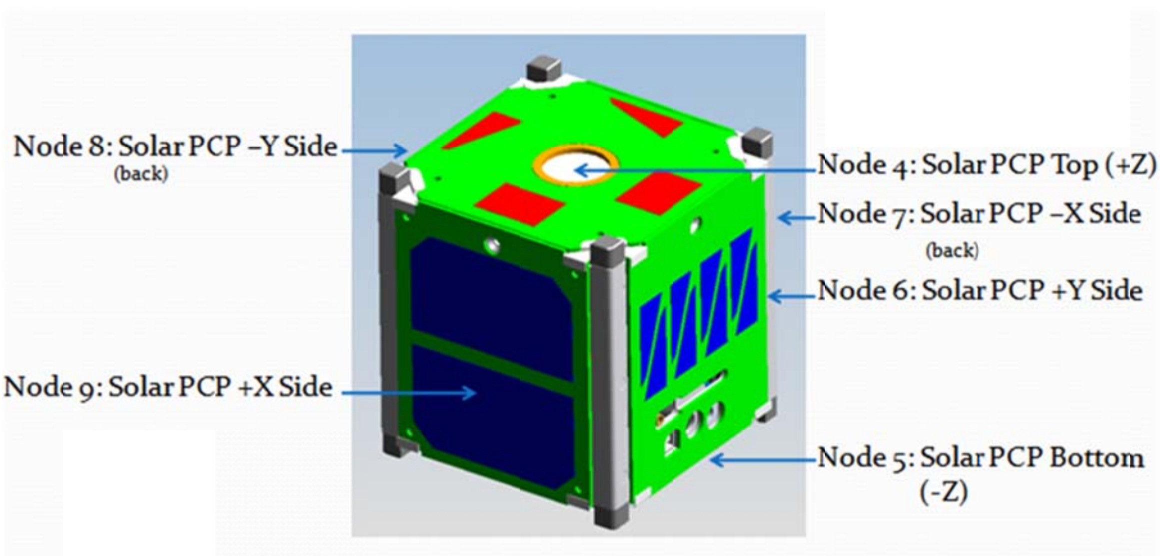

Figure 24 SCAT Thermal Analysis Nodes 4–9 (From [23])

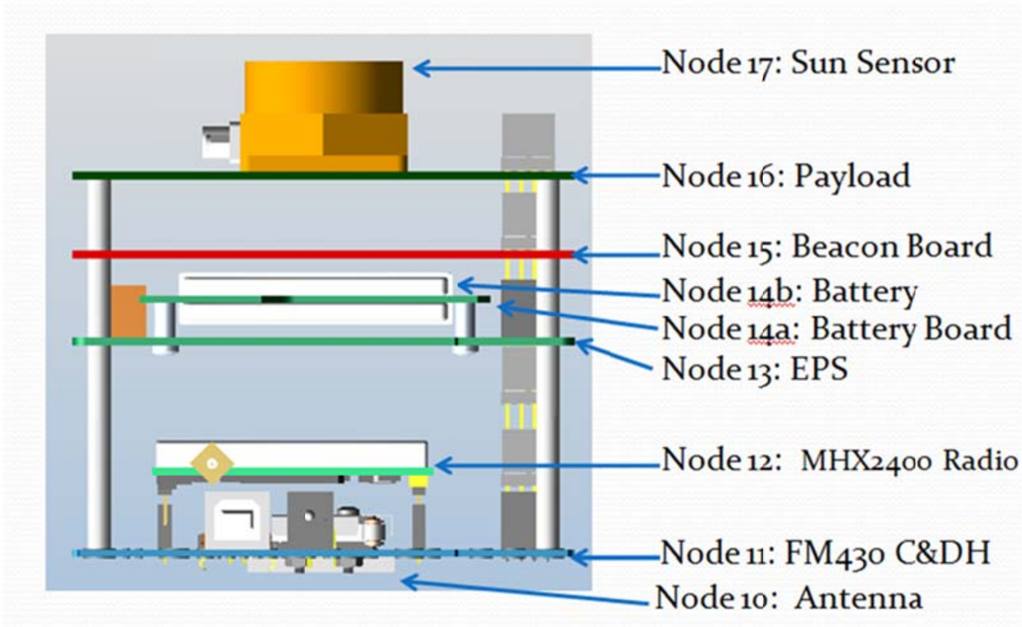

Figure 25 SCAT Thermal Analysis Nodes 10–17 (After [23])

2. Building Model Parts

The building of the model began by constructing a wire frame of parts in NX-6 I-deas Master Modeler mode. Master Modeler mode is a design system for geometric modeling of mechanical parts and allows for simplified construction of complex geometry. With exception of the sun sensor and patch antenna, each piece of the CubeSat was modeled as a two-dimensional element (paper thin). The "thickness" of each element was considered when the physical and material properties were entered during finite element modeling. Although SCAT consists of over 450 parts, only the 21 nodes were actually "built" in NX-6 I-deas to simplify the model.

The first step in building the model was to create the CubeSat structure which began with basic 1U CubeSat skeleton imported as a CAD overlay (IGS file) from the CubeSatKit website [25] (see Figure 26). The second step was to populate the model with each subsystem printed circuit board (FM430, MHX2400, EPS, Battery, Beacon, Payload). Each board was measured and dimensions entered to the nearest tenth of a millimeter. Next, the six solar panels were constructed in the CAD model in addition to their respective solar cells. Lastly, the sun sensor and patch antenna were modeled and placed appropriately.

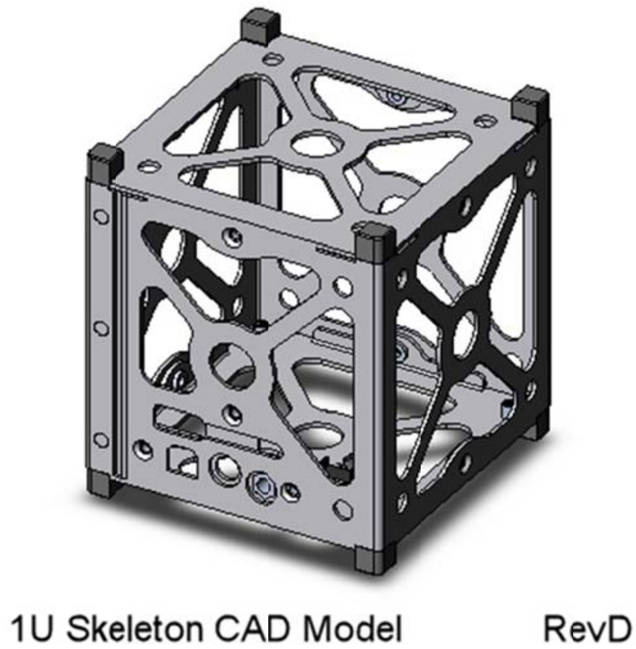

Figure 26 CubeSat Structure (From [25])

The following assumptions / methods were used to simplify the model:

1. All six sides of the CubeSat structure were modeled as if having the same shape (they were similar). SCAT uses a custom made base plate and cover plate. A CubeSat Kit CAD model for the custom plates did not exist at the time this model was created.

2. The data bus connector was considered invisible, but was taken into account when calculating heat conduction from one board to another.

3. Each TASC cell was modeled as a perfect triangle of equivalent area and the eight TASC solar cells on the +Y board were considered one large cell of equivalent area.

4. The FM430, EPS, Beacon, and SMS boards were all considered to be perfectly rectangular (i.e., no side cutouts) and identical in size.

5. The MHX2400, Battery Board and Battery were also considered to be perfectly rectangular.

6. Boards were measured at their mid-height point to calculate distance between boards. However, these boards were still considered 2-D.

7. The sun sensor was assumed to be completely cylindrical (it had a hexagonal base).

8. The beacon antenna was not modeled as the design had not been finalized.

Once all the parts were completed, they were assembled into one satellite compilation using Master Assembly mode which allows manipulation of the satellite in subassemblies.

3. Finite Element Model

The next step was to create a finite element model from the SCAT CAD assembly of parts; this is also known as "meshing." The basic idea is to discretize an infinite dimensional problem with a finite representation. The Master FEM mode of NX-6 I-deas directly uses the wireframe assembly for construction of a finite element model. A picture of the SCAT FEM is shown in Figure 27.

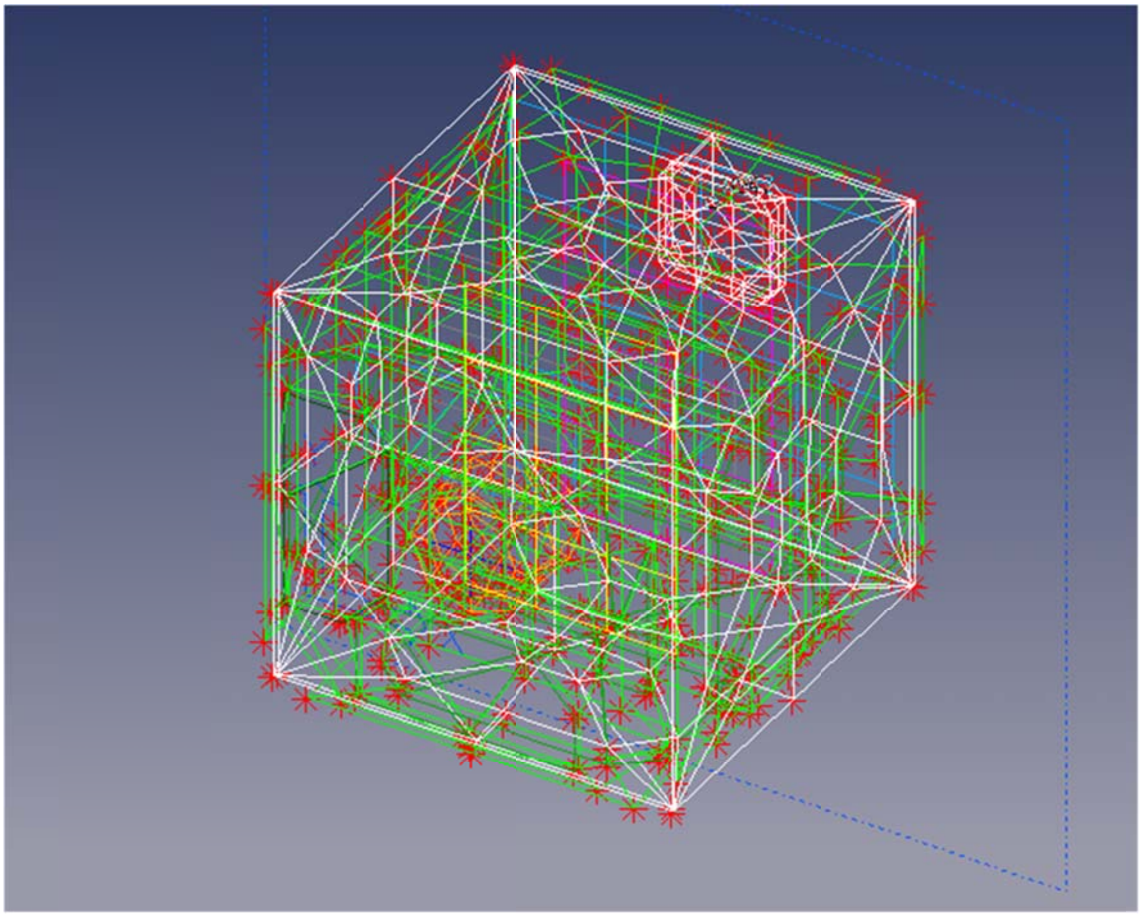

Figure 27 SCAT Finite Element Model—576 Elements and 738 Nodes

Meshing was done one part at a time and required two steps: (1) define the number and shape of finite elements, and (2) enter the thickness and material of the part. As part of the discretization process, each part was broken down into subpieces called elements. The intersections between elements were called nodes. These 738 finite element nodes are the common junctions between finite elements and should not be confused with the 21 thermal nodes that were previously defined for SCAT as representing average temperatures and thermal masses of components. The basic principle for defining finite elements was to break it down into the minimum number of elements needed. If the elements were too small, the model would take too long to process or worse, the computer would run out of memory before completing the analysis. If the elements were too large, the model would not have the desired fidelity.

Defining the shell mesh could be accomplished with the NX-6 I-deas auto-meshing feature or by manually entering the nodes and elements. When practical, auto-meshing was used to save time. However, some of the surfaces were curved or had irregular angled parts and in these cases, the auto-meshing function created an unacceptably high number of elements. Therefore, the mesh of these nodes and elements was manually defined to simplify the model. When complete, the SCAT FEM consisted of 576 elements and 738 nodes. Examples of some meshed parts are shown in Figures 28, 29, 30, 31, 32, and 33.

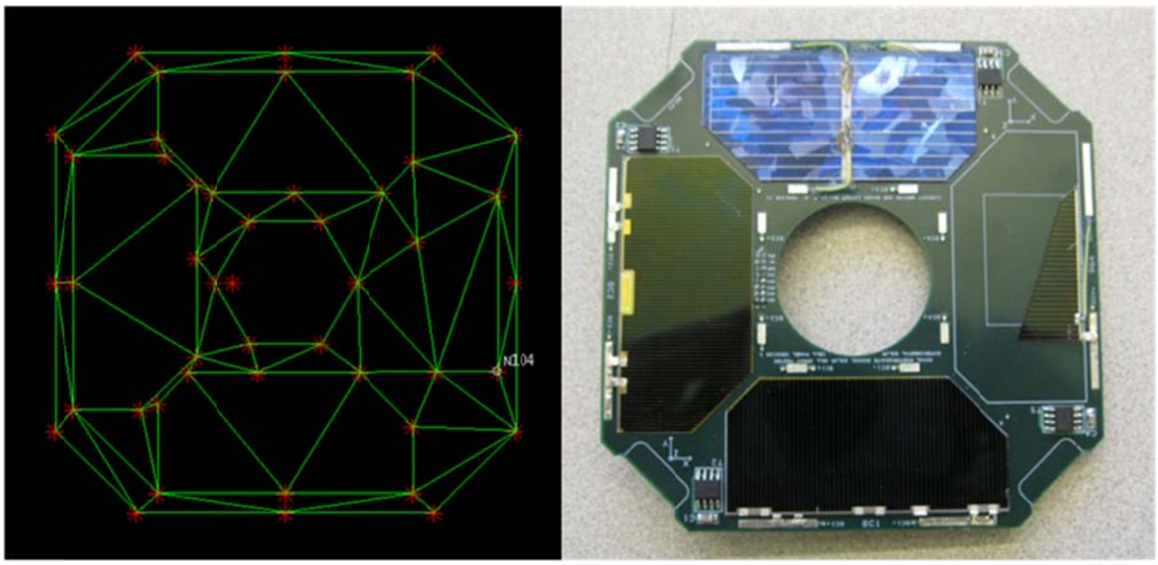

Figure 28 SCAT Experimental Solar Panel FEM

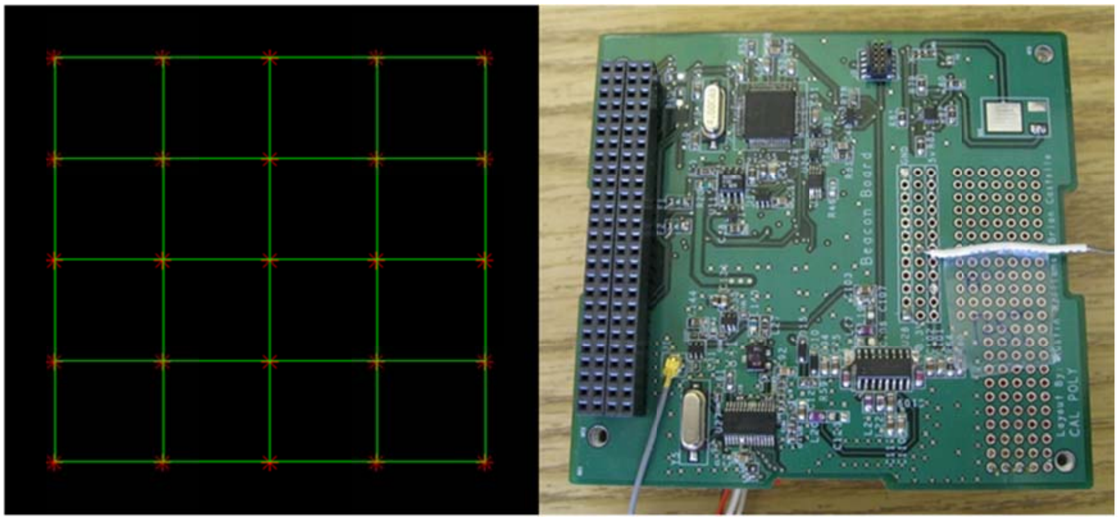

Figure 29 Generic PCB FEM

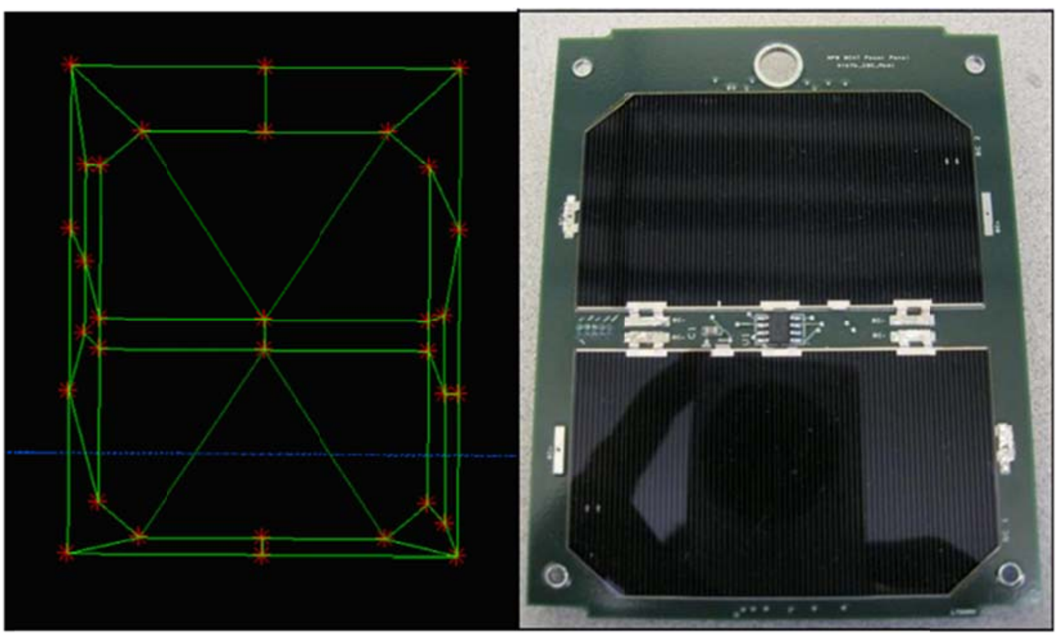

Figure 30 SCAT Solar Panel FEM

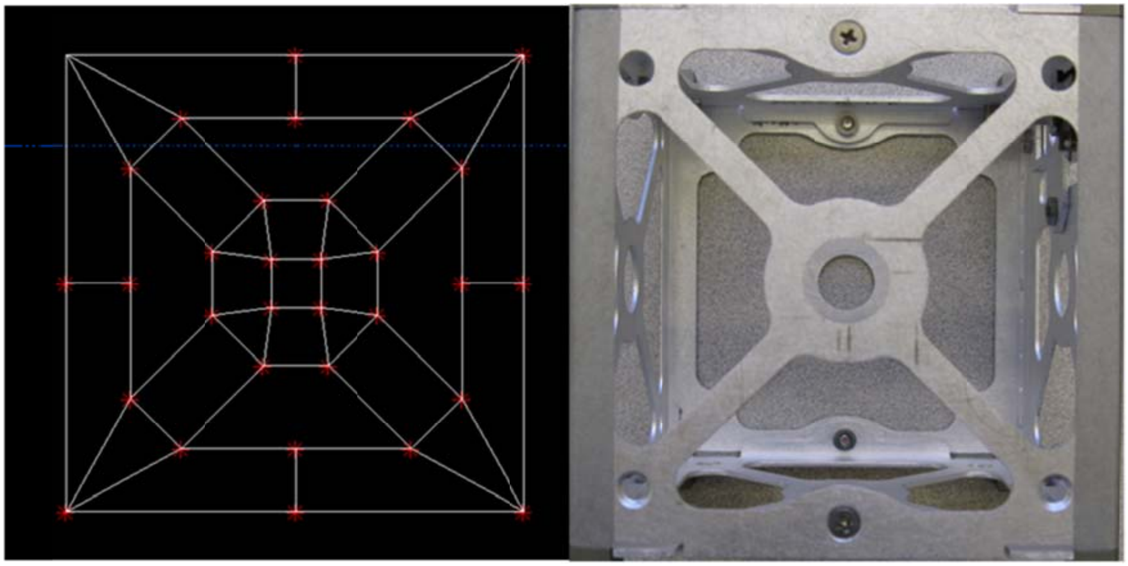

Figure 31 SCAT Structure Side FEM

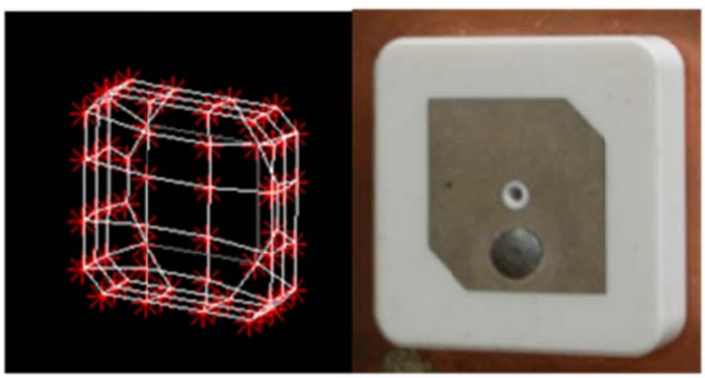

Figure 32 Patch Antenna FEM

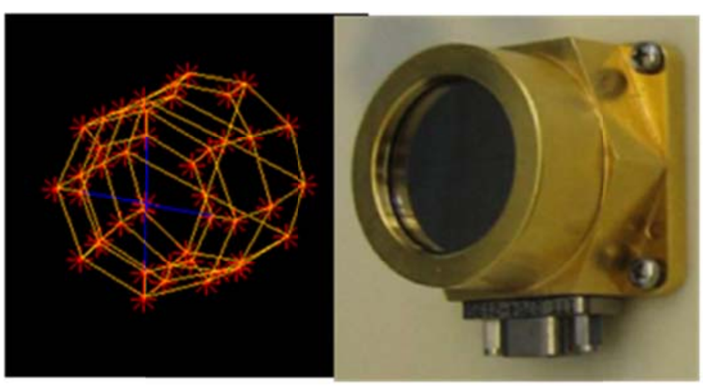

Figure 33 Sun Sensor FEM

4. Material and Physical Properties

The second step in meshing was to define the thickness and material of each part. NX-6 I-deas has a catalog of common materials and their average physical properties. However, the majority of SCAT materials were unique and were not found in the catalog. The physical and optical properties of these materials would need to be entered separately. To execute thermal analysis on the SCAT model, the following values needed to be obtained : material, thickness, density (ρ), thermal conductivity (k), specific heat (C_p), absorptivity (α) and emissivity (ε).

Data collection of these properties proved to be challenging and extremely time consuming. Some materials were easily identified while others required contacting the manufacturers of a component. Thicknesses were measured using digital calipers when possible. If the thickness of a material could not be easily measured, the thickness was estimated. Some components, such as solar cells, were made from several layered materials which required some creative interpolation of each layer's optical properties to produce one set of generalized properties. Other components, such as the patch antenna and sun sensor optic, were fabricated with manmade materials whose optical and physical properties were unpublished. In these cases, the published material properties of similar elements were used instead.

While a complete table of SCAT's material and physical properties is included in Appendix D, the following assumptions and methods were used when defining the optical and physical properties:

1. BTJM and Silicon solar cells are assumed to have the same emissivity and absorptivity as ITJ cells.
2. The absorptivity of FR-4 is equal to its emissivity.
3. The absorptivity of Gold and Silver were assumed to be three times their emissivity.
4. The emissivity and absorptivity of synthetic sapphire (SMS optic material) was unknown and thereby estimated by the manufacturer.

5. The absorptivity of alumina is similar to that of alumina on inconel.

6. The sun sensor support (not the optics) was assumed to me made entirely of gold.

7. The thickness of the aluminum foil covering the battery cells is 0.1 mm.

The sun sensor and the patch antenna required separate calculations since they were not modeled as 2-D elements. NX-6 I-deas uses the entered thickness and density values to calculate the mass of the component. Since the masses of the sun sensor and the patch antenna were known (34 g and 18.7 g, respectively), the "thickness" value was back calculated using the densities of the materials.

5. Radiation

Once the FEM was created, the next step was to define the directions of radiation for each component. In theory, all components radiate in all directions. However, in NX-6 I-deas radiation is unidirectional (unless specified otherwise), and the default direction for radiation is outward. Since most SCAT components were modeled as 2-D, they would radiate in both the inward and outward directions. Therefore, the "reverse side" radiation was turned on for all components except the patch antenna, sun sensor, battery and solar cells.

The patch antenna and sun sensor were modeled in 3-D and therefore they did not radiate inward. Additionally, both components were flush mounted directly onto other surfaces. That meant that on the mounted side, the sun sensor and patch antenna conducted, not radiated, to those surfaces. The radiation directions for the sun sensor and patch antenna are depicted in Figure 34 and Figure 35.

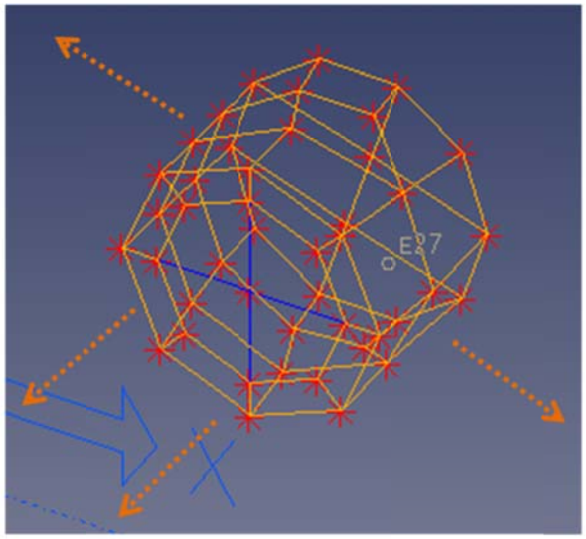

Figure 34 Sun Sensor Radiation Directions

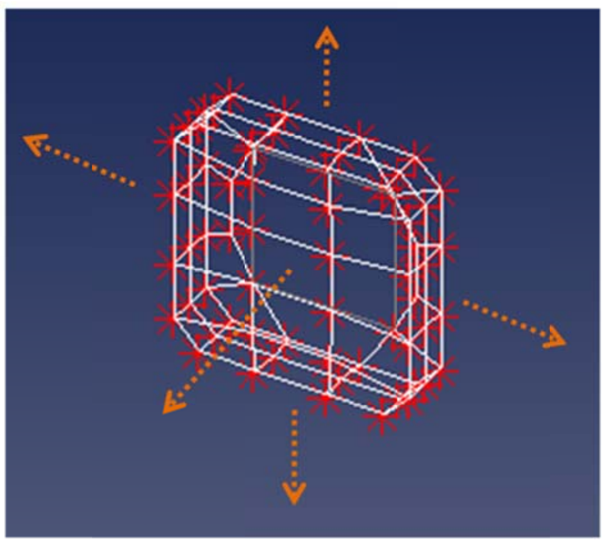

Figure 35 Patch Antenna Radiation Directions

Although the battery and solar cells were modeled in 2-D, radiation was only defined in the outward direction because they were flush mounted directly to other surfaces. The battery was mounted with adhesive and soldered tabs to the battery board. Each solar cell was mounted with double-sided kapton tape to the solar panel PCBs.

6. Conduction

The next step in creating the thermal model is to define the conduction paths within the satellite where heat flows from a region of higher temperature to a region of lower temperature. This is done in two parts: (1) building the conduction matrix and (2) calculating the resistance between components.

a. Conduction Matrix

The conduction matrix outlines how heat travels between satellite components via conduction. This matrix was created by defining which components directly contacted another component and their method of conductivity. For simplicity, some of the conduction paths that would transfer negligible amounts of heat were ignored in this thermal model and are suggested for future work.

The following connections were outside the scope of this thermal model and are not included in the conductivity calculations:

1. The clips that hold the solar PCBs to the structure
2. The SMS panel Samtec, Hirose and Mini D Connectors
3. The MHX 2400 and Beacon Board Coax Cables
4. The separation switch cable
5. The four soldered tabs that hold the battery cells to the battery board

The conduction matrix and list of conduction paths is shown in Appendix E.

b. Calculating Thermal Resistance

Once the conduction matrix has been defined, the next step is to quantify the thermal conductance between nodes. NX-6 I-deas is capable is using either thermal conductance (G) or thermal resistance (R_T) values to determine the amount of conduction between nodes.

The relationship of thermal conductance to thermal resistance is defined below (see Equation 5-3).

$$G = \frac{1}{R_T} \tag{5-3}$$

In this thermal model, thermal conductivity was used when available. Otherwise, the thermal resistance was calculated using Equation 5-4 where L is the length of the conduction path, k is the thermal conductivity and A is the cross-sectional area.

$$R_T = \frac{L}{kA} \tag{5-4}$$

In some cases, the conduction path consisted of a series of multiple connections (i.e., screw, into a threaded tube, into a screw). In the case of multiple piece connections, the total resistance (R_{Total}) is equivalent to the summation of each piece in series (see Equation 5-5).

$$R_{Total} = R_1 + R_2 + R_3 + \ldots \tag{5-5}$$

Multiple connections will also have contact resistance between each piece. Thermal contact resistance is difficult to measure and rarely given in the specifications by the manufacturer. However, electrical contact resistance is more commonly provided and is measured in ohms (Ω). Electrical contact resistance is included as part of the total electrical resistance (R_e). If the manufacturer does not provide the electrical contact resistance parameter, it could theoretically be determined with an ohm-meter capable of measuring very small electrical resistances. Due to limitations in lab equipment, this measurement was unattainable for some connections.

The Wiedemann-Franz law states that the ratio of the thermal conductivity (k) is proportional to the electrical conductivity (σ) at a given temperature [26]. Using the following relationships and rearranging Equations 5-4 and 5-7, we arrive at Equation 5-8.

ρ =electrical resistivity (Ωm)

σ =electrical conductivity ($\frac{1}{\Omega m}$)

R_e =electrical resistance (Ω)

$$\rho = \frac{1}{\sigma} \tag{5-6}$$

$$R_e = \rho\left(\frac{L}{A}\right) \tag{5-7}$$

$$R_T = \frac{R_e}{\rho k} \tag{5-8}$$

In the case of the FM430 to MHX2400 bus connectors and the CubeSat Kit bus connectors, the contact resistance was given as 0.01Ω. The total thermal resistance calculations for all the parts are displayed in Appendix F.

7. Thermal Boundary Conditions

The last step in creating the thermal model is to define the thermal boundary conditions. The thermal boundary conditions are described by identifying any component that emits heat by characterizing its power consumption. SCAT's power consumption matrix is shown in Table 10.

Table 10 SCAT Power Matrix

Node	Description	Power Req'd (ON) (W)	Power Req'd (Xmit)(W)	Power Req'd (Stby) (W)
1	Structure +Y side	0	0	0
2	Structure Top	0	0	0
3	Structure Bottom	0	0	0
4	Solar PCB +Z	0	0	0
5	Solar PCB -Z	0	0	0
6	Solar PCB +Y	0	0	0
7	Solar PCB -X	0	0	0
8	Solar PCB -Y	0	0	0
9	Solar PCB +X	0	0	0
10	Patch Antenna	0	0	0
11	FM430	0.014	0.014	0.014
12	MHX 2400 Radio	1.102	1.312	0.017
13	EPS	0.21	0.21	0.21
14a	Battery PCB Board	0	0	0
14b	Batteries	0	0	0
15	Beacon Board	0.08	1.95	0.08
16	Payload (SMS)	0.1299	0.1299	0.1299
17	Sun Sensor	0	0	0
18	Structure -X side	0	0	0
19	Structure -Y side	0	0	0
20	Structure +X side	0	0	0

For the purposes of the SCAT thermal model, the FM430, EPS and SMS were considered always ON. The duty cycle for the MHX2400 and the Beacon will vary slightly on orbit but on average they exhibit a 13% duty cycle [21].

The SCAT EPS also utilizes battery heaters to prevent the batteries from exceeding their low temperature limit of -20˚ C during discharge. A thermostat boundary condition was included in the thermal model which defined the battery heater’s total heat load of 0.2 watts with a cut-in temperature of 0˚ C and a cut-off temperature of 5˚ C [27].

VI. THERMAL MODEL ORBIT SIMULATION

A. FEM THERMAL MODEL

1. Orbit Simulation Parameters

The last step in the thermal design process is to run the thermal model using orbit simulation. At the time the thermal model was completed, SCAT was expected to launch as a secondary payload into a circular orbit with altitude of 450 kilometers, an inclination of 45 degrees and an orbital period of 93.58 minutes. The date of the launch was still pending.

Two orbital simulations were completed: one for the worst hot case and one for the worst cold case. Orbital parameters for each case are shown in Table 11.

Table 11 Thermal Model Orbital Parameters

	Cold Case	Hot Case
Beta Angle	0 degrees	68.4 degrees
Sun Position	June Solstice	December Solstice

To simulate the space environment, the radiation control was set to "space enclosure" with a constant temperature of -269˚ C. The spacecraft orientation was set to rotate about an axis 45˚ off of its geometric center. The rotation rate was set to 60 revolutions per orbit which equates to about 3.6˚ per second. Due to the enormous amount of data generated and the limited memory of the computer, the thermal model was run for two orbits, providing data at a constant time interval of 12 seconds.

2. Satellite Temperature Limits

SCAT's various subsystems have different operating temperature limitations. As can be seen from Table 8, the Lithium Ion Polymer battery cells are the most restrictive. This battery has a minimum temperature of 0˚ C and a maximum temperature of 45˚ C while charging. During discharge, the battery has a minimum temperature of -20˚ C and a maximum temperature of 60˚ C. The battery can be expected to discharge when the satellite is in eclipse and charge when exposed to the sun. For thermal analysis purposes, the battery design temperature range will be 0˚ C to 45˚ C since that is the most restrictive and it is unknown exactly when the satellite will be charging or discharging.

3. Thermal Model Validation

Due to the complexity of the thermal model and the nature of the tumbling spacecraft in orbit, it was important to validate the thermal model in the simplest orbit prior to proceeding to the expected orbit hot and cold case scenarios. Four different orbits and spacecraft tumbling configurations of increasing complexity were run prior to the final scenarios (see Table 12). The external panel temperatures were analyzed and compared against each scenario to ensure that the results were logical. Orbits 1 through 4 are described in this section. The final cold and hot case scenarios are detailed in the following section.

Table 12 Thermal Model Validation Scenarios

Orbit #	Beta Angle	Spacecraft Rotation
1	90	None
2	0	None
3	90	About Y-Axis (0,1,0)
4	90	About (1,1,1)
Cold Case - FINAL	0	About (1,1,1)
Hot Case - FINAL	68.4	About (1,1,1)

a. Orbit 1 (Beta = 90, No Rotation)

The simplest scenario to validate was for a beta angle equal to 90˚ and a non-rotating spacecraft. This initial conditions placed the –X side of the CubeSat towards the sun and it maintained that orientation throughout the orbit (Figure 36). Thermal model results from the orbit 1 scenario are shown in Figure 37.

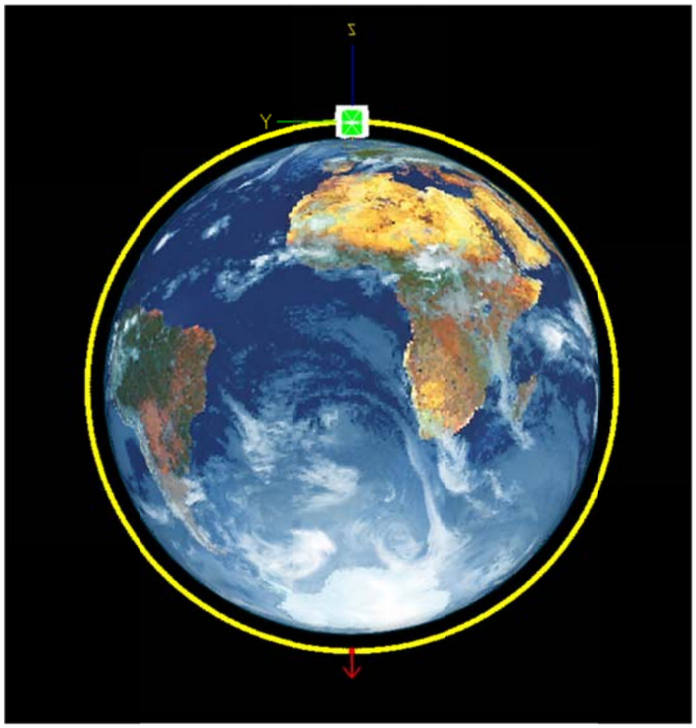

Figure 36 View of Orbit 1 From the Sun (Beta = 90, No Rotation)

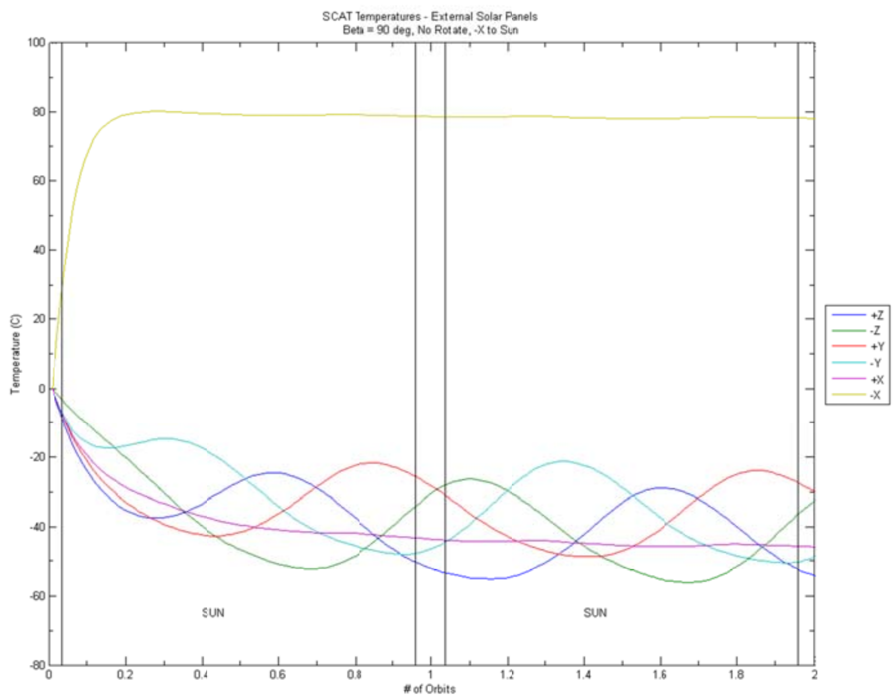

Figure 37 Thermal Model Results—Orbit 1 (Beta = 90, No Rotation)

In this scenario, the –X side of the spacecraft is exposed to the direct sun at all times. As expected, the –X panel is the hottest panel; it's temperature increases to approximately 80˚ C upon the commencement of the orbit simulation (after starting at the initial conditions of 0˚ C) and stays there for the remainder of the simulation. The +X side is never exposed to direct sun but has a view factor of deep space the majority of the orbit. This accounts for its plateau at a cold temperature of approximately -43˚ C. The remaining four sides (_Y, -Y, +Z, -Z) never see direct sun, but are subject to the Earth's albedo once per orbit which keep the spacecraft very cold on average. These results are consistent with what a typical spacecraft would experience and validate the thermal model in this scenario.

b. Orbit 2 (Beta = 0, No Rotation)

The next scenario validated was for a beta angle equal to 0˚ and a non-rotating spacecraft. This initial conditions placed the –X side of the CubeSat towards the sun and it maintained that orientation throughout the orbit (Figure 38). Thermal model results from the orbit 1 scenario are shown in Figure 39.

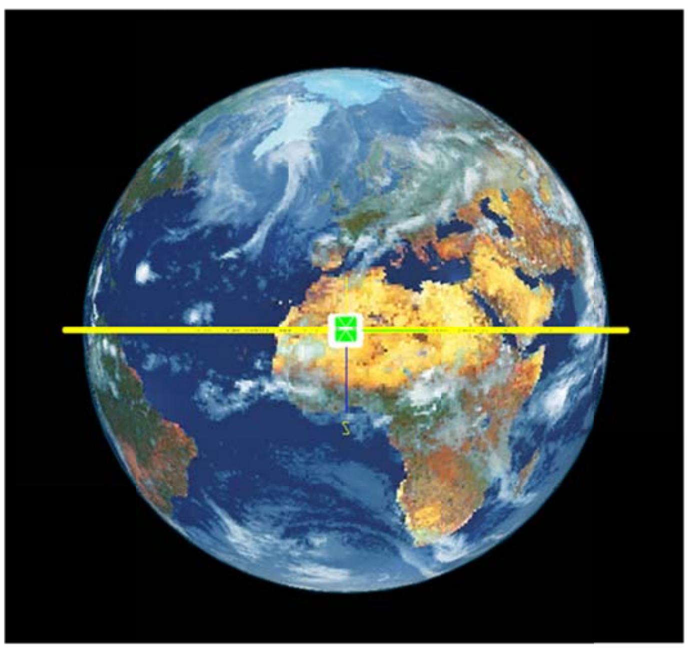

Figure 38 View of Orbit 2 From the Sun (Beta = 0, No Rotation)

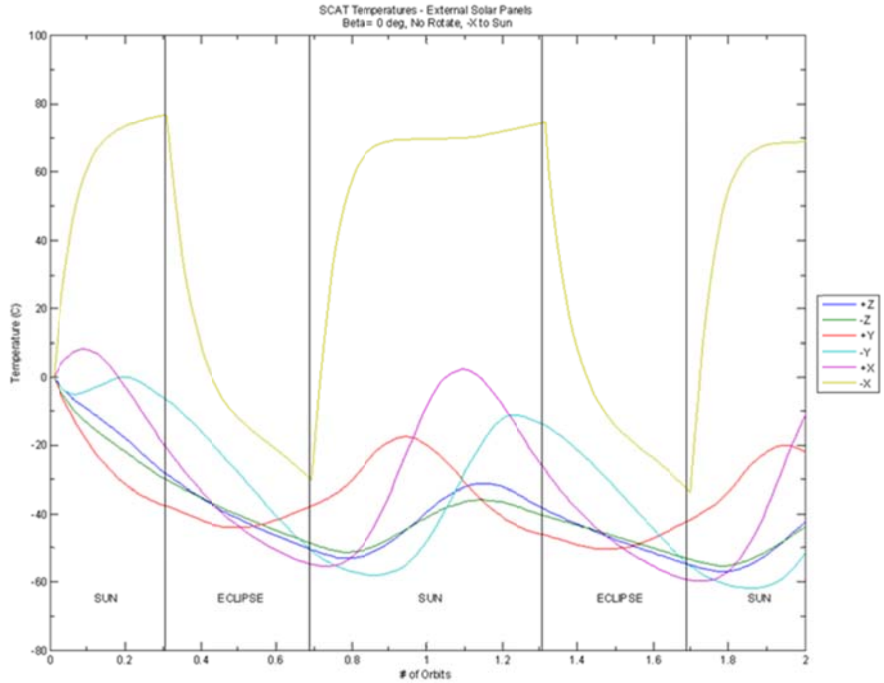

Figure 39 Thermal Model Results—Orbit 2 (Beta = 0, No Rotation)

As expected, the –X side of the spacecraft receives the most direct heating from the sun, only to cool down when it retreats into the earth's eclipse. The +X side receives no direct exposure to the sun, however it is subject to the radiative heating of the earth (albedo) when in the sun and is exposed to deep space in eclipse. The +Y and –Y external panels are on the left and right side of the spacecraft as viewed from the sun. These panels are not exposed to direct sun but are subject to the earth's albedo and deep space on opposite sides of the orbit which account for their moderately cold temperatures. The +Z and –Z faces are on the top and bottom of the CubeSat, respectively. These sides never see direct sun or earth albedo, which accounts for their extreme cold temperatures.

c. Orbit 3 (Beta = 90, Rotate About Y-Axis)

Once the thermal model was validated for the nonrotating case, the next step was to rotate the spacecraft about a simple axis. In this case, the Y-Axis was chosen as the test case. Again, the CubeSat was initialized in the same orientation as the previous scenarios: the –X side of the spacecraft initially facing the sun. The spacecraft was then rotated about the Y-axis, like a rotisserie, at a rate of 60 rotations per orbit which equates to 3.6 degrees per second. The thermal model results are shown in Figure 40.

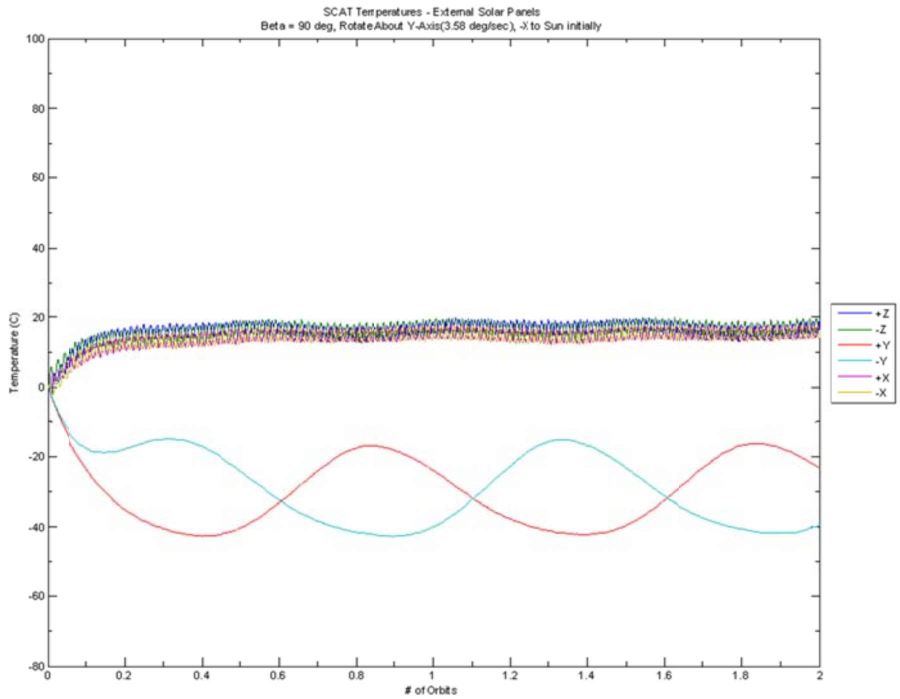

Figure 40 Thermal Model Results—Orbit 3 (Beta = 90, Rotate about Y-Axis)

Since the +X, -X, +Z and –Z sides are all exposed to the identical amount of sun, earth albedo and deep space, they are expected to have similar temperatures. As can be seen from the figure above, these four sides all maintain temperatures fluctuating between approximately 10˚ C and 18˚ C. The +Y and –Y sides are facing left and right as seen from the sun and therefore never see direct sunlight. Their only source of heat is from exposure to the Earth’s albedo once per orbit. Consequently, these sides are very cold, averaging approximately -30˚ C.

d. Orbit 4 (Beta = 90, Rotate About 1,1,1 Axis)

The last scenario evaluated prior to running the actual expected orbit was when beta = 90 and the spacecraft rotated about an oblique axis of 1,1,1 at 3.6 degrees per second. The CubeSat was subject to the same initial conditions as the previous three orbits. The results of the thermal model are shown in Figure 41.

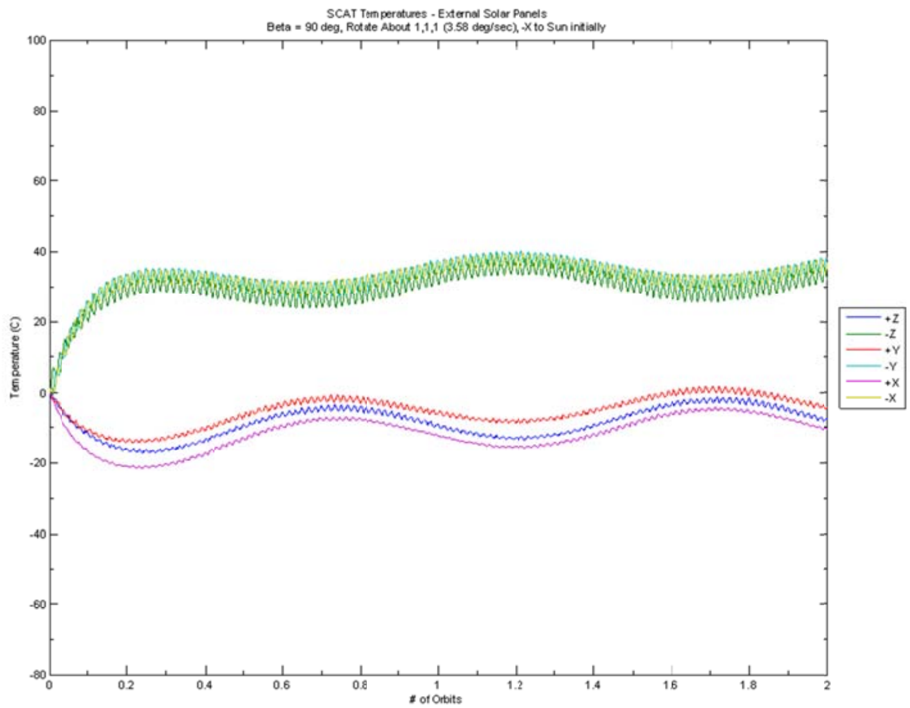

Figure 41 Thermal Model Results—Orbit 4 (Beta = 90, Rotate About 1,1,1 Axis)

By rotating the spacecraft about the 1,1,1 axis, the -X, -Y and -Z faces will be fully exposed to direct sunlight once per spacecraft rotation. Similarly, the +X, +Y and +Z panels will be exposed to deep space once per spacecraft rotation. Due to the rapid rotation rate of 3.6 degrees per second, each "plus face" will be exposed to the identical amount of sun, albedo and deep space. This results in each "plus face" being similar in temperature to the other "plus faces" as will the "minus faces" be similar to eachother. As can be seen from the figure above, the "plus faces" remain fairly warm with an average temperature of approximately 33˚ C. The variations in temperature are due to the exposure to the Earth's albedo once per orbit. Additionally, the "minus faces" remain fairly cold with an average temperature of -10˚ C. Their temperature fluctuations per revolution are minor since these faces are never directly exposed to the sun.

4. Orbit Worst Case Cold / Hot Scenario Results

The thermal model orbit simulation was run two additional times for three full orbits and provided worst case hot and cold temperatures for each component of the satellite. A screen shot of a "second in time" of the orbit simulation is shown in Figure 42 and the min/max component temperature results are presented in Table 13 and Table 14.

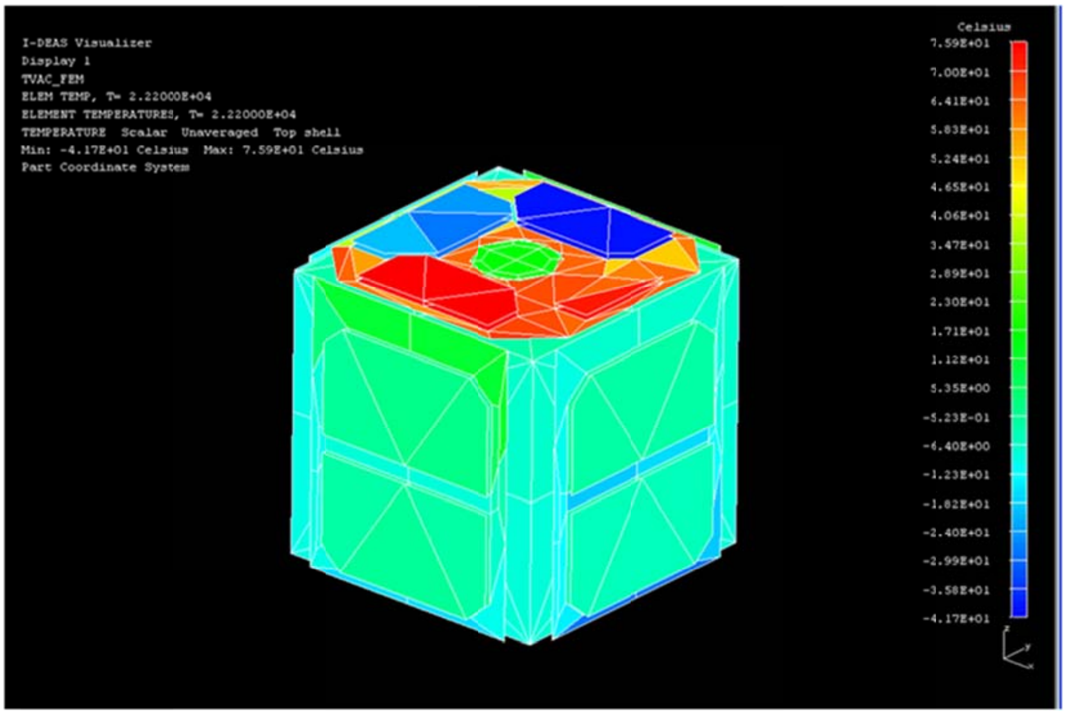

Figure 42 NX-6 I-Ideas Thermal Model in Orbit Simulation—Screen Shot

Due to limitations of the NX-6 I-deas program, it is impossible to put SCAT in a completely random tumbling orbit. The best representation of SCAT's attitude in orbit is to give the CubeSat a set rotation about the 1,1,1 axis. This results in the -X, -Y, and -Z faces being exposed to the sun once per revolution and the +X, +Y, +Z sides being subject to deep space once per revolution. This limitation results in the "minus faces" being the warmest and the "plus faces" being the coldest of the external panels. In cases where the plus side is similar to the minus side, it can be assumed that these results are relatively interchangeable. The plots of the external panel temperatures for the hot and cold cases are shown in Figures 43 and 44.

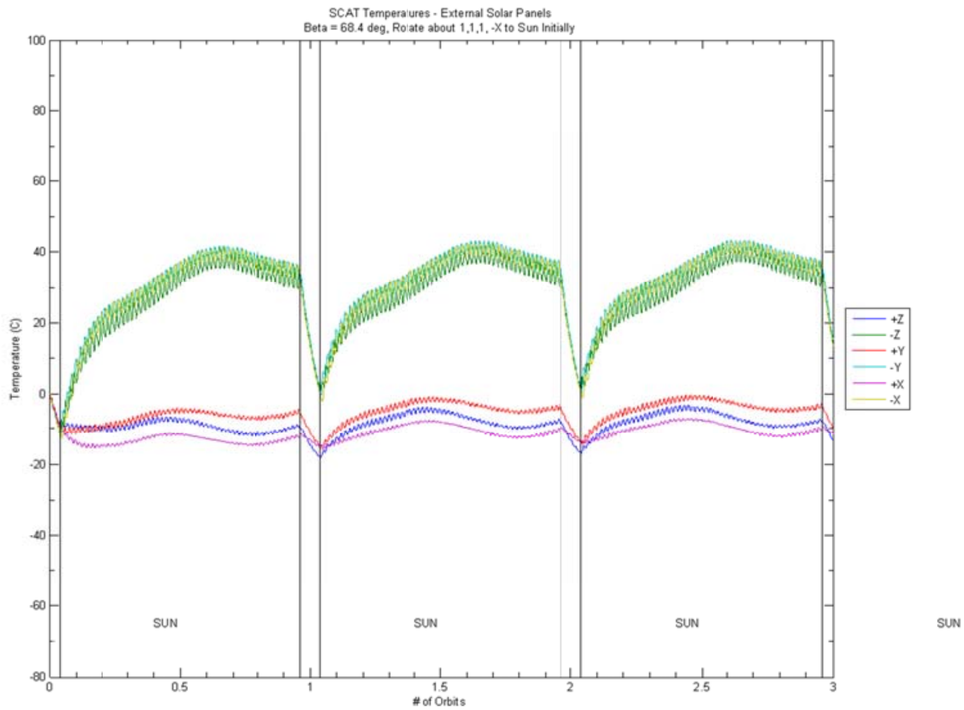

Figure 43 Thermal Model of External Panels—Worst Hot Case

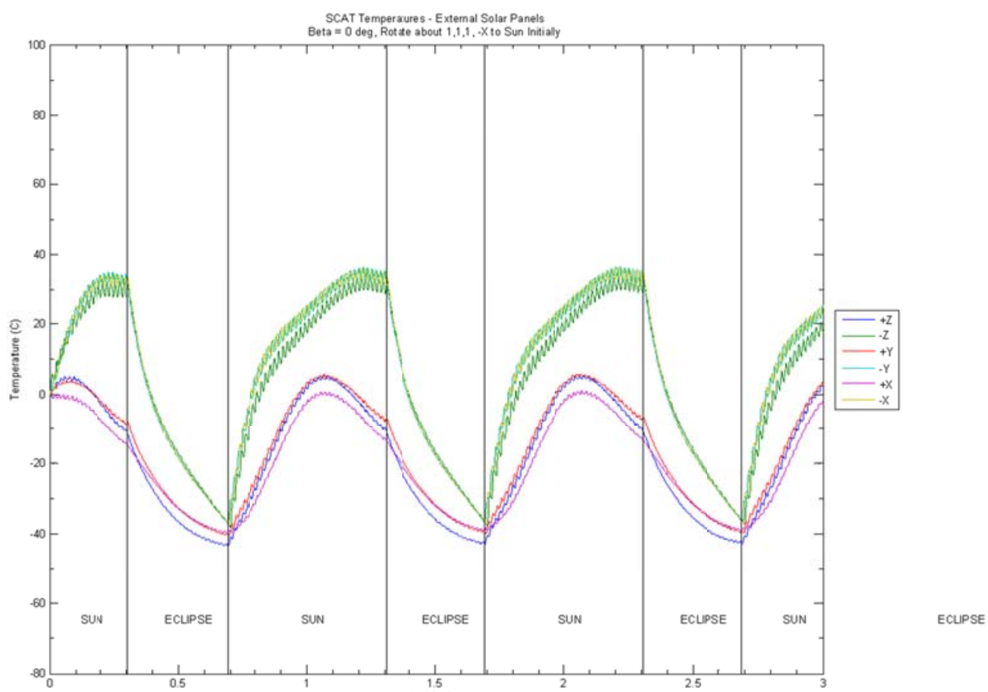

Figure 44 Thermal Model of External Panels—Worst Cold Case

For the worst hot case, all subsystem components were predicted to be within acceptable temperature limits. For the worst cold case, the +Z PCB and +Y PCB are predicted to reach temperatures below the minimum acceptable operating range. The PCBs have an operating temperature limit of -40˚ C due to the op-amp, voltage converters and molex connectors. A discussion of the results is given in section VI.C.

Table 13 SCAT Thermal Model Temperature Range: Worst Hot Case

Node	Description	Tmin(˚C)	Tmax(˚C)
1	Structure +Y side	-3.0	13.8
2	Structure Top	-4.4	11.5
3	Structure Bottom	-0.1	18.9
4	Solar PCB +Z	-18.1	-3.8
5	Solar PCB -Z	0.1	40.7
6	Solar PCB +Y	-15.5	-0.9
7	Solar PCB -X	-2.1	42.9
8	Solar PCB -Y	-0.3	43.3
9	Solar PCB +X	-15.4	-7.6
10	Patch Antenna	-0.6	20.1
11	FM430	19.1	43.8
12	MHX 2400 Radio	15.6	40.3
13	EPS	8.8	31.6
14a	Battery PCB Board	3.5	29.0
14b	Batteries	4.1	27.5
15	Beacon Board	7.7	27.1
16	Payload (SMS)	0.6	17.3
17	Sun Sensor	0.4	17.1
18	Structure -X side	-0.2	18.5
19	Structure -Y side	-0.2	18.3
20	Structure +X side	-3.1	13.3

Table 14 SCAT Thermal Model Temperature Range: Worst Cold Case

Node	Description	Tmin(˚C)	Tmax(˚C)
1	Structure +Y side	-22.5	7.5
2	Structure Top	-23.4	5.5
3	Structure Bottom	-21.0	11.8
4	Solar PCB +Z	**-43.4**	5.4
5	Solar PCB -Z	-38.0	33.7
6	Solar PCB +Y	**-40.4**	5.8
7	Solar PCB -X	-37.2	36.2
8	Solar PCB -Y	-37.1	36.5
9	Solar PCB +X	-39.9	0.8
10	Patch Antenna	-21.1	13.2
11	FM430	-1.5	35.2
12	MHX 2400 Radio	0.1	31.7
13	EPS	1.1	20.9
14a	Battery PCB Board	0.2	16.4
14b	Batteries	3.8	15.6
15	Beacon Board	2.7	17.8
16	Payload (SMS)	-1.3	5.6
17	Sun Sensor	-1.4	5.3
18	Structure -X side	-21.6	11.6
19	Structure -Y side	-21.9	11.4
20	Structure +X side	-22.3	7.1

SCAT's battery is the most sensitive to temperature extremes. However, based upon the thermal model, the battery will not experience any temperatures that exceed the operating temperatures. Battery temperatures reach steady state after three orbits. Plots of the worst hot and cold case battery temperatures are shown in Figure 45 and Figure 46.

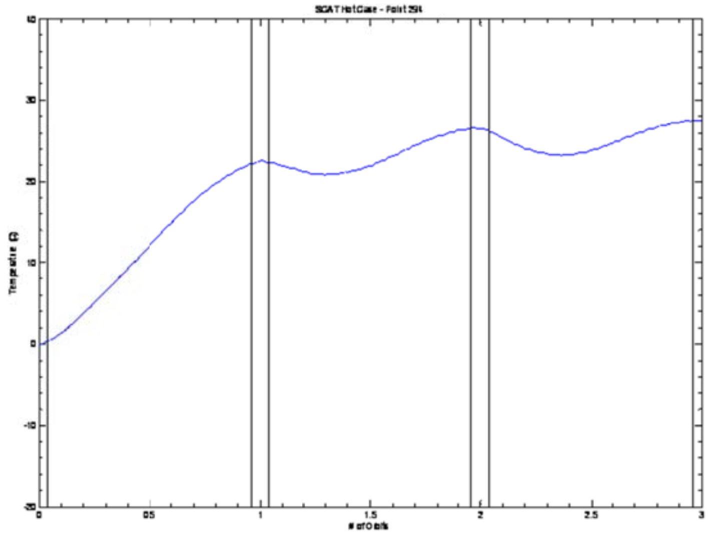

Figure 45 Thermal Model of Battery—Worst Hot Case

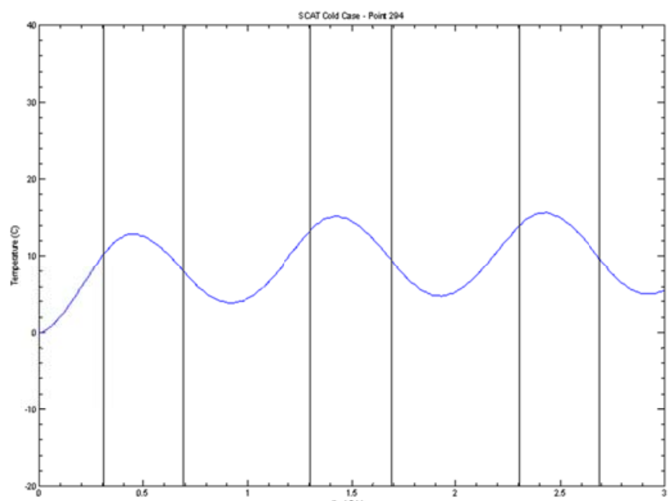

Figure 46 Thermal Model of Battery—Worst Cold Case

B. COMPARISON OF SINGLE NODE THERMAL MODEL VS. FEM

The single-node thermal model was created by the SCAT Systems Engineer, LT Rod Jenkins, and the detailed calculations of that model are documented in his thesis [7]. In short, it was a simplified model that assumed the entire satellite was one single thermal node. The orbital parameters used in this model were similar to those used in the CAD model: circular orbit with an altitude of 450 kilometers, inclination of 45˚, and beta angles of 0˚ to 68.4˚. A plot of the temperature versus beta angle, displaying the upper and lower temperature limits for the model, is shown in Figure 47.

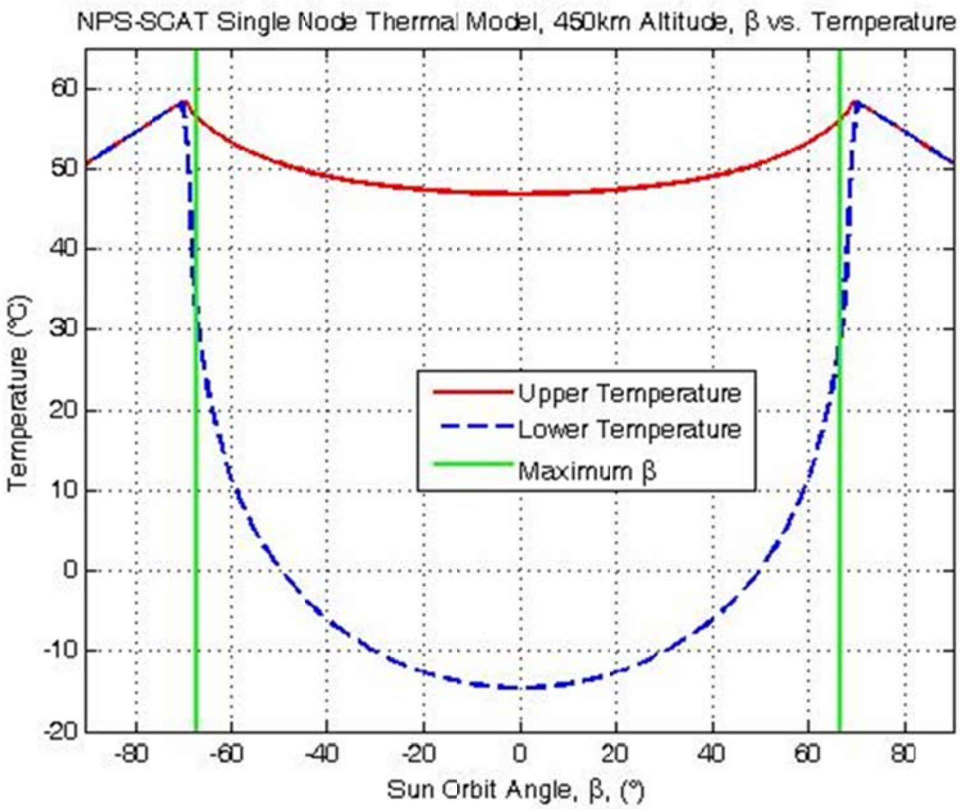

Figure 47 Single Node Thermal Model Beta Angle Vs. Temperature (From [7])

The results of the single-node model predicted extreme temperatures of 47˚ C to -15˚ C for the cold case (beta = 0˚) and 56˚ C to 28˚ C for the hot case (beta = 68.4˚) [7]. A point in the midsection of the SCAT NX-6 I-deas model was used for comparison (element # 192). The maximum and minimum temperatures predicted at this point in the NX-6 I-deas model are presented in the Tables 15 and 16.

Table 15 Thermal Model Comparison—Cold Case

Thermal Model	Min Temp (˚ C)	Max Temp (˚ C)
Single-Node Model	-15	47
NX-6 I-Ideas Model(1)	-2	35

Note: (1) Max / Min temperatures are for SCAT Element 192

Table 16 Thermal Model Comparison—Hot Case

Thermal Model	Min Temp (˚ C)	Max Temp (˚ C)
Single-Node Model	28	56
NX-6 I-deas Model(1)	19	44

Note: (1) Max / Min temperatures are for SCAT Element 192

As can be seen from Table 16, the NX-6 I-deas thermal model predicts narrower temperature spans than the single node model. For the cold case, the NX-6 I-deas model calculates minimum / maximum cold case temperatures of 12˚ hotter and 12˚ colder than the single-node model, respectively. The hot case NX-6 I-deas model predictions show a maximum temperature 12˚ colder and a minimum temperature 9˚ colder than the single node model. These differences are most likely caused by the simplification of the single-node model and the fact that it represents the entire satellite (inner and outer) with a single temperature node. The single-node model results are useful by providing a "ballpark" estimate that can be used for determining thermal testing conditions. Yet, it does not provide predicted temperatures for individual components and therefore, its usefulness in designing a thermal control system is minimal.

C. NX-6 I-DEAS THERMAL MODEL CONCLUSIONS

It was expected that all six sides of the satellite would have a consistent (or at least similar) thermal response in the model. This expectation was based upon the fact that the satellite's internal components ("the stack") were modeled with the heat signature spread uniformly throughout each PCB and that the satellite was a free tumbling satellite with consistent radiation exposure to the sun, earth and deep space. Since the solar panels are very similar in their design and materials, this difference in temperatures is due to the fact that the thermal model does not have each side being uniformly exposed to the space environment. The reason for this inconsistency in the temperature of the solar panels is because the simulation would not allow for a free tumbling spacecraft. The thermal model was defined as having a rotation axis 45˚ off its geometric center. This resulted in high and low temperatures on the solar panels that may not be truly representative of a randomly tumbling CubeSat. It is surmised that each external panel of the satellite could possibly get as hot or as cold as any other side. Therefore, it is recommended that the thermal model temperatures for each external panel are assumed to be possible for all panels.

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VII. THERMAL MODEL TVAC SIMULATION

A. SIMULATION PARAMETERS

After completion of the TVAC testing, the thermal model was run with the TVAC temperature profile. The objective was to validate the accuracy of the model by comparing the results of the TVAC test and the TVAC simulation. The thermal model was adjusted to account for the satellite setup as well as simulate the thermal vacuum chamber temperature profile.

First, the component duty cycle was changed in the model so that it was equivalent to the test setup. During the TVAC test, the FM430, EPS and SMS were always ON and therefore modeled as such. The MHX2400 was operating on an altered duty cycle of 60 seconds OFF, 6 seconds ON, and 4 seconds of XMIT to transmit component temperature and voltage data to the test engineers every 70 seconds. Additionally, the beacon board was OFF as it was not functional during the time of thermal testing. The battery heater thermostat boundary condition was adjusted to characterize the actual cut-in / cut-off temperatures of -7˚ C and -4˚ C, respectively. Although the battery was periodically charged using a USB charging cable, no changes to the model to account for this. See Table 17 for a summary of duty cycles.

Table 17 TVAC Simulation Component Duty Cycles

Component	Duty Cycle
FM 430	Always ON
EPS	Always ON
SMS	Always ON
MHX 2400	60 seconds OFF 6 seconds ON 4 seconds XMIT
Beacon	Always OFF

Second, the environment in the thermal model was altered to represent the TVAC temperature as it changed throughout the test. The radiation control was set to "space enclosure" with a time varying temperature table. In order to determine the TVAC temperature profile, a thermocouple (T3) was attached to the left wall of the chamber and temperature data was recorded every 15 seconds. The temperature profile is shown in Figure 48. A table of the temperature profile is listed in Appendix G.

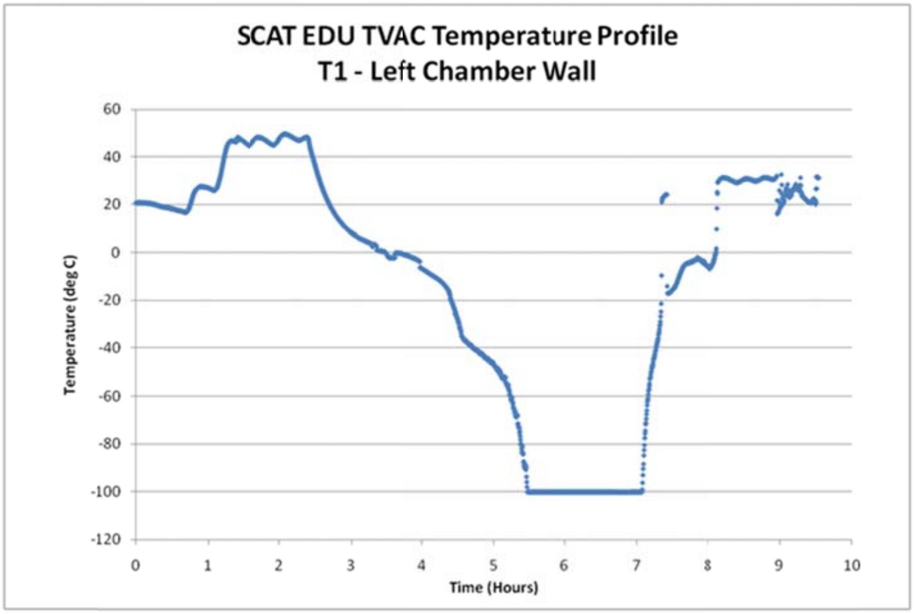

Figure 48 TVAC Temperature Profile

Of note, the T1 thermocouple measured the temperature of the chamber at exactly -100˚ C during cold soak for approximately 1 ½ hours. After the test was complete, it was discovered that the T-type thermocouples used with the Omega HH-147 data logger had a temperature range of -100˚ C to 400˚ C [28].. Due to the range limitation of the thermocouples, the actual temperature profile below -100˚ C was unknown. The ultimate low temperature capability of the TVAC chamber is published as -73˚ C [29].

Lastly, the original spacecraft rotation/tumble rate and orbital parameters were suppressed in the TVAC simulation scenario. The thermal model was run for a total of 34200 seconds (or 9 ½ hours, consistent with the TVAC test) and provided data at a constant time interval of 30 seconds.

B. SIMULATION RESULTS

1. Thermal Model TVAC Scenario Results

The time history temperature predictions for the thermal model run with the TVAC profile are shown in Figure 49. These thermal model results are the forecast of what temperatures would be experienced by each component when SCAT was put in the thermal vacuum chamber and exposed to the TVAC temperature profile. These results are compared with the actual TVAC results in the subsequent section.

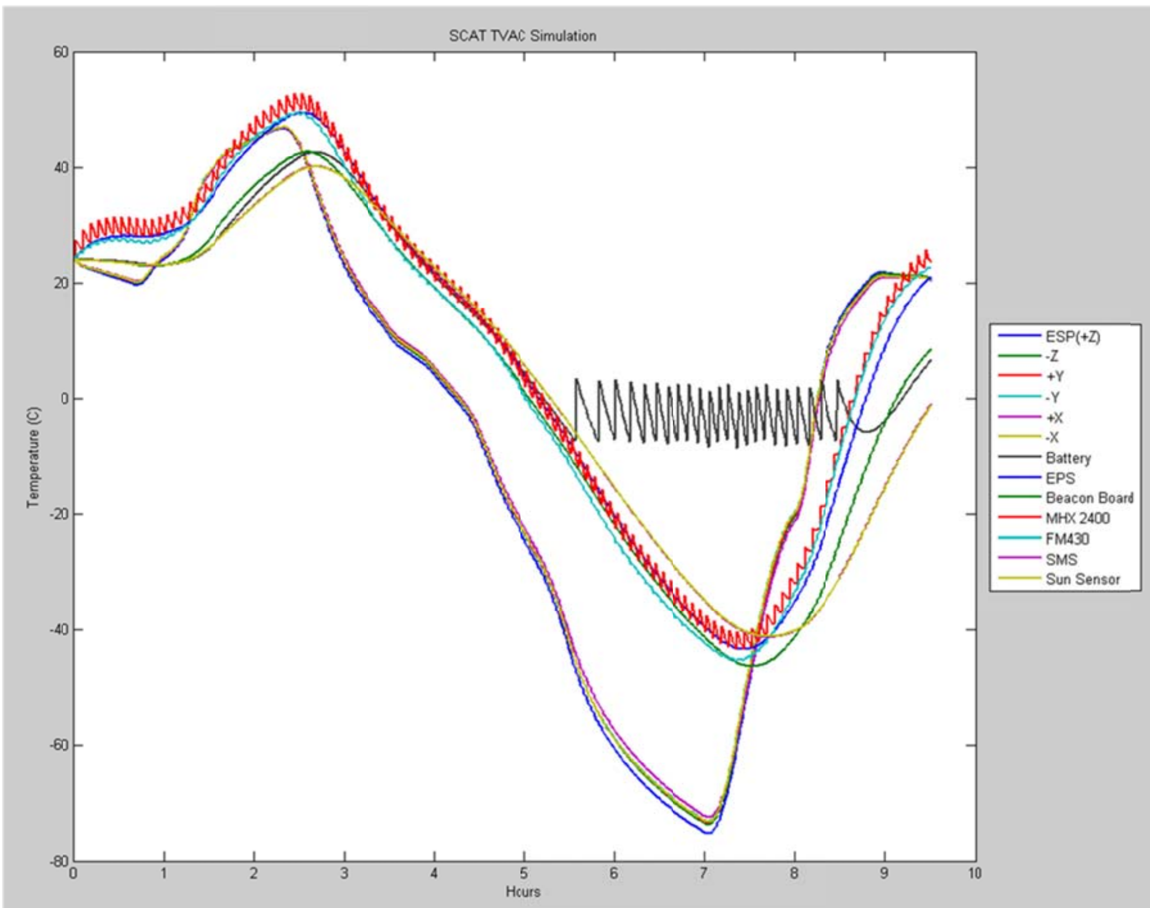

Figure 49 Thermal Model TVAC Simulation Results

In Figure 49, there are three noticeable groupings of temperature profiles: (1) External Solar Panels; (2) SMS, Sun Sensor and Beacon Board; and (3) EPS, MHX 2400 and FM430. In the first obvious grouping, the thermal model predicts that the external solar panels (+X, -X, +Y, -Y, +Z, -Z) will experience a temperature swing of ~120˚ C with a temperature of approximately 46˚ C during hot soak and -73˚ C during cold soak. The second grouping shows the SMS, Sun Sensor and Beacon Board experiencing a much narrower temperature oscillation of approximately 40˚ C to -40˚ C. The third grouping of the EPS, MHX 2400 and the FM430 predict they will experience temperatures from 50˚ C to -43˚ C. Of note, the regular, small scale cycling of the MHX 2400 profile denotes the MHX 2400's TVAC duty cycle which turns the radio ON / OFF every 70 seconds (see Table 17 for the detailed duty cycle). Additionally, the predicted battery profile represents the battery heater turning ON/OFF during cold soak as it keeps the battery from exceeding its temperature limits.

2. Comparison of TVAC Test Results Vs. Thermal FE Model

The thermal model results were then compared with the actual data observed from the TVAC test. A comparison of the time history temperature results for each subsystem are shown in Figure 50 through Figure 52. In general, the results agree pretty well, given the difficulty of accurate thermal modeling. In particular, the model and the TVAC test results have the same shape, the peaks occur at the same time, and the hot soak temperatures are quite close. However, there are significant temperature differences during the cold soak. For example, the SMS temperature difference at hot soak was ~2.5˚ C, but during cold soak that temperature difference increases to approximately 31˚ C. Possible causes for this temperature differential are discussed in the next section.

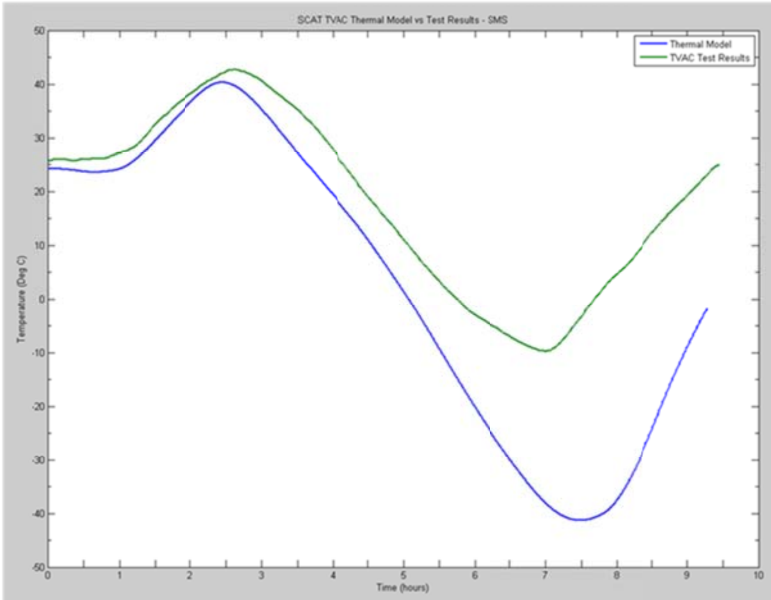

Figure 50 Comparison of Thermal Model Vs. Test Results—SMS

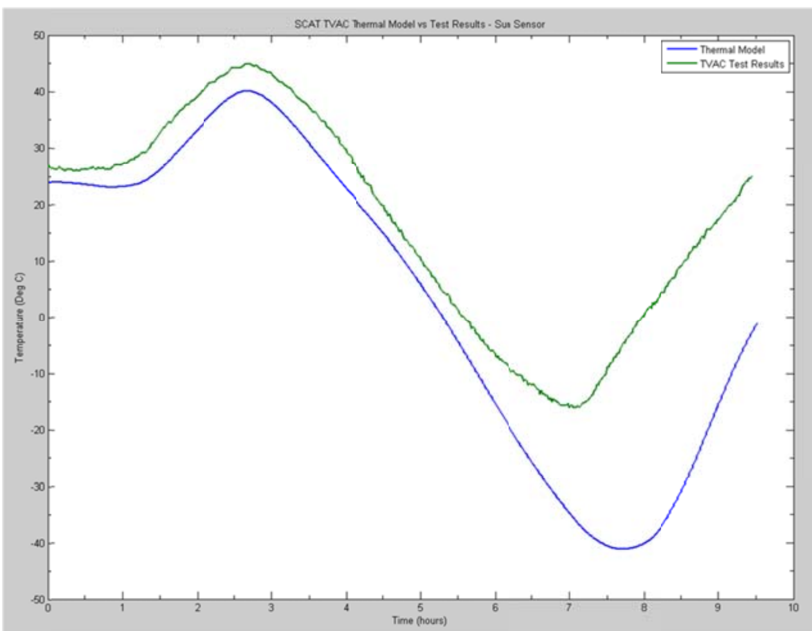

Figure 51 Comparison of Thermal Model Vs. Test Results—Sun Sensor

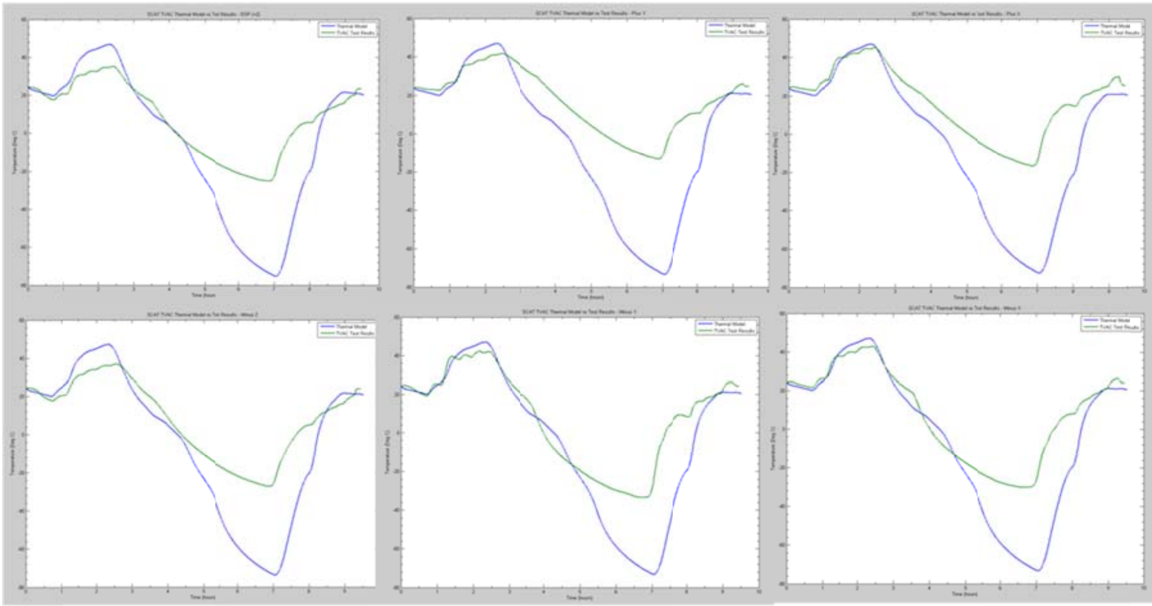

Figure 52 Comparison of Thermal Model Vs. Test Results—External Solar Panels

For the battery, the cold soak temperatures of the model and the test results were much more consistent with peak hot / cold temperature differences of only ~1˚ C and ~1.5˚ C, respectively. Although the battery heater was modeled as having a cut-in / cut-off temperatures of -7˚ C and -4˚ C, the thermal model showed the battery cycling between approximately -8.5˚ C and +2˚ C. The reason for this disparity is unknown, and it is recommended that further thermal model analysis be completed to investigate the cause.

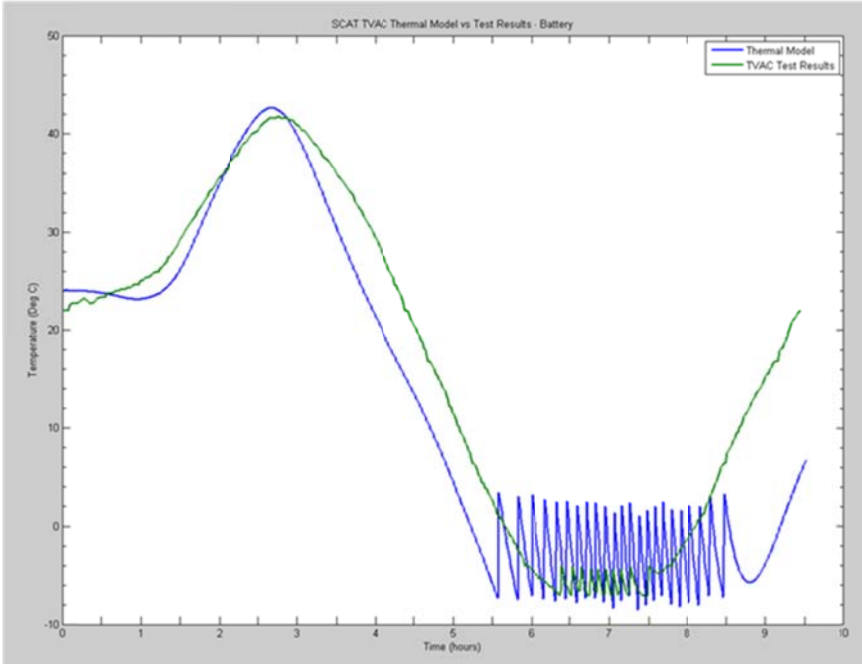

Figure 53 Comparison of Thermal Model Vs. Test Results—Battery

C. CONCLUSIONS

The temperature differences between the thermal model and the TVAC results were most likely caused by a combination of factors: (1) the simplification of the model compared to the complexity of the spacecraft; (2) the lack of test setup equipment accounted for in the model; and (3) inaccuracies in the TVAC temperature profile at the low end. A thermal model can never perfectly imitate a real satellite and Chapter IV discusses the assumptions made when creating the thermal model for NPS-SCAT. Additionally, the TVAC thermal model did not account for the thermocouples, wires and test harness, nor the periodic battery charging complete with the USB cable. Lastly, the TVAC temperature profile used in the model was based exclusively on the T1 thermocouple data that was attached to the left chamber wall. Most likely, the temperature in the chamber was not completely uniform throughout and a single temperature profile would not accurately describe the environment inside the chamber.

Of note, an additional thermocouple (T3) was placed on the right chamber wall, but its reading were inconsistent and unreliable. Recommendations for future tests include running the TVAC profile again with additional thermocouples placed in various locations throughout the chamber to get a more complete temperature profile.

VIII. CONCLUSIONS AND FUTURE WORK

A. SUMMARY

This thesis chronicles the design, execution and analysis of thermal environmental testing, and thermal modeling of the Naval Postgraduate School Solar Cell Array Tester CubeSat (NPS-SCAT) in preparation for launch into low earth orbit. As part of the satellite developmental process, a comprehensive test plan was developed and thermal vacuum testing was completed to predict SCAT's ability to survive and function in the space environment. To predict the satellite's thermal response in the space environment, a detailed thermal model was created in NX-6 I-deas to predict SCAT's component temperatures response in orbit. The thermal model and an environmental test program that were developed can serve as a baseline for CubeSat development, easily customized for future NPS CubeSats.

B. THERMAL TEST RESULTS

Thermal environmental testing was conducted so that satellite deficiencies could be discovered before launch. The thermal vacuum tests were performed in a TVAC chamber which allowed the satellite to be subjected to pressure and temperature changes similar to that of space. A hot soak and cold soak were performed to verify that the materials were suitable for space and ensure the workmanship of the satellite and subsystems was adequate for satellite survivability.

1. Thermal Vacuum Test

a. Conclusions

A qualification-level thermal vacuum test was completed on the NPS-SCAT Engineering Design Unit. This test included a single thermal cycle that reached a hot soak temperature of +40˚ C and a cold soak temperature of -33˚ C. The temperature critical satellite components (battery and sun sensor) were monitored throughout the test to ensure that no temperature limits were exceeded. It was also necessary to have a solid power management plan and to monitor the battery voltage during the test to prevent damage to the battery cells. The thermal chamber was unable to bring the satellite to the desired cold soak qualification temperature of -42˚ C within several hours. Since it took over 3 hours to reach -33˚ C, the entire satellite experienced very low temperatures (more so than it would on orbit) and it was felt that a one hour cold soak at that temperature should be sufficient to demonstrate SCAT's survivability in the space environment.

b. Future Work

Although the TVAC test completed was thorough, there are still some improvements that should be made to the profile and hardware before future testing is conducted. First of all, the beacon board was still in the development phase at the time of TVAC testing and therefore, was not tested. Any follow-on testing should include a functioning beacon board. Secondly, future TVAC test conductors should consider using liquid nitrogen in the test chamber to help reach their cold soak temperatures more quickly, especially if their objective is below -30˚ C. Thirdly, the T3 thermocouple placed on the right wall of the chamber was unreliable and presented unrealistic temperatures if they were presented at all. Lastly, the temperature profiles of the external panels throughout the test revealed large differences between temperatures on each side of the satellite. This suggests that the thermal vacuum chamber does not heat and cool uniformly. It is recommended that the chamber be characterized to determine where the "hot spots" and "cold spots" are within it.

Before SCAT will be ready for launch, a final thermal vacuum test of the flight unit and the flight back-up unit will need to be conducted. These tests should be completed in accordance with an appropriate test standard such as MIL-STD-1540E, which calls for four thermal cycles at acceptance levels with a minimum temperature range of 100˚. Once a launch opportunity is secured, the temperature levels will be defined by the projected orbit and launch vehicle specifications.

2. Thermal Model Test

a. Conclusions

The NX-6 I-deas thermal model was run with the TVAC temperature profile and testing duty cycles. The results were compared with the actual data observed from the TVAC test to validate the thermal model and verify the TVAC's temperature profile. In general, the model and the TVAC test results had the same shape and the peaks occurred at the same time, validating the thermal model. However, a comparison of the time history temperature results showed that the model predicted SCAT's external panels may reach temperatures much colder than actually experienced. Due to temperature overshoot, the battery thermal model predicted that the battery heater would cycle between approximately -8.5˚ C and +2˚ C during testing but actual TVAC testing showed that the battery heater kept the battery temperature between -7˚ C and -4˚ C.

The temperature differences between the thermal model and the TVAC results were most likely caused by a combination of factors: (1) the simplification of the model compared to the complexity of the spacecraft; (2) the lack of test setup equipment accounted for in the model; and (3) inaccuracies in the TVAC temperature profile. The largest contributor to the differences in temperatures is most likely the inaccuracies in the TVAC temperature profile which was based exclusively on the T1 thermocouple data that was attached the left chamber wall. The additional thermocouple (T3) was unreliable during the test and did not provide useful chamber temperature data. Most likely, the temperature in the chamber was varying throughout and a single temperature profile would not accurately describe the environment inside the chamber.

b. Future Work

The comparison of TVAC thermal model results and actual test results revealed that the chamber temperature profile was not representative of the temperatures SCAT experienced inside the chamber. A recommendation for future testing would include running the TVAC test against with additional thermocouples placed in various locations throughout the chamber to get a more complete temperature profile.

Additionally, it is recommended that further thermal model analysis be completed to investigate the cause of the disparity in battery heater temperatures.

C. THERMAL MODEL ORBIT SIMULATION

A satellite thermal finite element model was developed in NX-6 I-deas to analyze and predict SCAT's component thermal response in the space environment. It was created to reveal situations when spacecraft component temperature limits would be exceeded, resulting in possible spacecraft degradation or mission failure. The satellite was divided into 21 thermal nodes, each representing a temperature and thermal mass. The material, physical, and thermal properties of each component were entered and the thermal boundary conditions defined. The model was run with the orbit parameters for a previously scheduled launch on the Falcon 1e, subsequently canceled. The thermal model orbit simulation was run over several orbits and provided worst case hot and cold temperatures for each component of the satellite.

1. FE Thermal Model Orbit Simulation

a. Conclusions

For the worst hot case, the thermal model orbit simulation calculated that all subsystem components would be within acceptable temperature limits. For the worst cold case, the +Z PCB and +Y PCB are predicted to reach temperatures below the minimum acceptable operating range. Although SCAT's battery is the most sensitive to temperature extremes, based upon the thermal model, the battery will not experience temperatures that exceed the operating temperatures.

The six external solar panels of the satellite did not have exactly the same thermal response in the model. Since the solar panels are very similar in their design and materials, this difference in temperatures is most likely due to the fact that the thermal model does not have them being uniformly exposed to the space environment. The main reason for the differences in the temperature of the solar panels is that the simulation would not allow for a free tumbling spacecraft.

The thermal model orbit simulation results are believed to be representative of what will actually be experienced on orbit. This determination was made after comparing the thermal model temperature results with those of two other on orbit CubeSats with similar characteristics, Cal Poly's CP-6 [20] and Aerospace Corporations' AeroCube-3 [30]. Both of these satellites are in orbits very similar to that expected for SCAT and have similar external panel temperatures. As can be seen in Table 18, SCAT's thermal model predicts temperatures from -37 (cold case) to +43 (hot case). While this is a larger temperature spread than AeroCube-3 and CP-6, the thermal model is limited in the CubeSat's orientation and therefore provides results that are slightly hotter and colder than most likely will be experienced.

Table 18 Comparable CubeSat External Panel Temperatures On Orbit

Satellite		Orbit	Min Temp (˚ C)	Max Temp (˚ C)
SCAT Thermal Model	Hot Case	450 km x 45˚	-18˚	43˚
	Cold Case	450 km x 45˚	-37˚	36˚
AeroCube-3		450 km x 40˚	-16˚	36˚
CP-6		450 km x 40˚	-27˚	23˚

b. Future Work

Although the SCAT thermal model was comprehensive and had results consistent with expected on-orbit temperatures, it is recommended that some minor adjustments be made to the model. In the model, SCAT was defined as having a rotation axis 45˚ off its geometric center. For future work, it is recommended that the thermal model simulation be run again with different rotation axes to validate the results. Additionally, it is recommended that the model be updated with actual beacon board power consumption values and that the beacon antenna be added to the model once the design has been finalized.

2. Comparison of FE Model Vs. Single-Node Thermal Model

a. Conclusions

The results of the NX-6 I-deas thermal model were compared with the single-node thermal model created by the SCAT Systems Engineer. The hot case I-deas model predictions showed a maximum temperature 12˚ colder and 9˚ colder than the single node model, and the cold case I-deas thermal model predicted a cold case temperature 12˚ hotter and 12˚ colder than the single-node model. These differences are most likely caused by the simplification of the single-node model. In summary, the single-node model results are accurate enough for determining thermal testing temperature range requirements, but not sufficient for determining the temperature profiles of individual components or designing a thermal control system.

b. Future Work

No future work is recommended with respect to the single-node thermal model.

APPENDIX A. SCAT TEST MATRIX

Component Testing				
Event	**Configuration**	**Testing Location**	**Test Level & Duration**	**Remarks**
Component-FT	Single S/S PCB	NPS SSL	Varied	As Necessary (before and after Vibe/TVac)
Component-TVac	Single S/S PCB	NPS—Bullard	On Orbit Temp. Range	Necessary for unqualified hardware/boards
Component-Vibe	Single S/S PCB	NPS—Halligan	NASA GEVS Workmanship	Necessary for unqualified hardware/boards

EDU Testing				
Event	**Configuration**	**Testing Location**	**Test Level & Duration**	**Remarks**
EDU-CFT-SS (x2)	EDU-SS	NPS SSL	N/A	As Necessary (before and after Vibe/TVac)
EDU-Vibe-SS	EDU	NPS—Halligan Hall	NASA GEVS Qualification	Verify structural integrity. CFT Required Pre/Post Test.
EDU-TVac-SS	EDU	NPS—Bullard Hall	Qualification On—Operational Off—Workmanship	
EDU-CPT-SS	EDU	NPS SSL	N/A	After EDU environmental testing complete. Use tilt table to rotate satellite through varying sun angles.

Flight Unit Testing				
Event	**Configuration**	**Testing Location**	**Test Level & Duration**	**Remarks**
Flight-CFT (x2)	Flight Unit	NPS SSL	N/A	As Necessary (before and after Vibe/TVac)
Flight-Vibe	Flight Unit, Integrated in Dispenser	NPS—Halligan Hall	NASA GEVS Acceptance (or Protoflight if needed)	Verify structural integrity.
Flight-TVac	Flight Unit	NPS - Bullard Hall	Acceptance: On Orbit Temp Range	
Flight-CPT	Flight Unit	NPS SSL	N/A	After FU environmental testing complete. Use tilt table to rotate satellite through varying sun angles.
Integration-CFT (within Dispenser)	Flight Unit, Integrated in Dispenser	TBD	N/A	Post-Integration functionality check

FT—Function Test

TVAC—Thermal Vacuum Test

Vibe—Vibration Test

SS—EDU with Sun Sensor Mass Model installed

CFT—Comprehensive Functional Test

CPT—Comprehensive Performance Test

SSL—Small Satellite Lab

EDU—Engineering Design Unit

FU—Flight Unit

APPENDIX B. NPS-SCAT EDU TVAC PROCEDURES

Naval Postgraduate School		
Date: 9/22/10	Status: Final	Rev: 2.1

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

Naval Postgraduate School Solar Cell Array Tester (NPS-SCAT) EDU TVAC Procedure 2.1

by
CDR Kerry D. Smith, USN
and
Marissa Brummitt

SCAT Test Engineers

WARNING

This procedure contains safety critical operations.

Naval Postgraduate School		
Date: 9/22/10	Status: Final	Rev: 2.1

Signature Approval

I have read and approve of the following procedures prior to handling hardware or operating equipment.

Title	Name	Signature	Date
Test Engineer	Marissa Brummitt		
Test Engineer	Kerry Smith		
Quality Assurance	Rod Jenkins		
SSAG Supervisor	David Rigmaiden		

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Naval Postgraduate School		
Date: 9/22/10	Status: Final	Rev: 2.1

Revision Log

This log identifies those portions of this document, which have been revised since the original issue.

Rev Code	DESCRIPTION	DATE
1.0	Initial Release-Marissa Brummitt	4/25/10
1.1	Update – Marissa Brummitt	8/12/10
2.0	EDU Specific Procedure – Marissa Brummitt	8/25/10
2.1	Post-TVAC Update – Kerry Smith	9/22/10

Table of Contents

List of Figures

Acronyms

BCR	Battery Charge Regulator
C&DH	Command and Data Handling
CFT	Comprehensive Functional Test
CPT	Comprehensive Performance Test
EDU	Engineering Design Unit
EPS	Electrical Power Subsystem
GEVS	General Environmental Verification Specification
NASA	National Aeronautics and Space Administration
NPS	Naval Postgraduate School
NPS-SCAT	Naval Postgraduate School Solar Cell Array Tester
PCB	Printed Circuit Board
P-POD	Poly-Picosatellite Orbital Deployer
SC	Spacecraft
SCAT	Solar Cell Array Tester
SMS	Solar Cell Measurement System
TVAC	Thermal Vacuum

1 Document Information

1.1 Purpose

This document describes the procedure for thermal vacuum testing of the NPS-SCAT CubeSat in the Small Satellite Lab at the Naval Postgraduate School. These procedures are necessary for EDU Testing.

1.2 Scope

This procedure includes instructions for operation of the thermal vacuum chamber in the Small Satellite Lab, Bullard Hall room 106. All other tests and operations taking place before, during and after the test can be referenced in the SCAT Test Plan, Comprehensive Performance Test or Comprehensive Functional Test.

1.3 Test Item

The test item is the NPS-SCAT EDU. This satellite does not have a functioning beacon board. The beacon board consists of the correct PCB with only deployment circuitry.

1.4 Task Flow Diagram

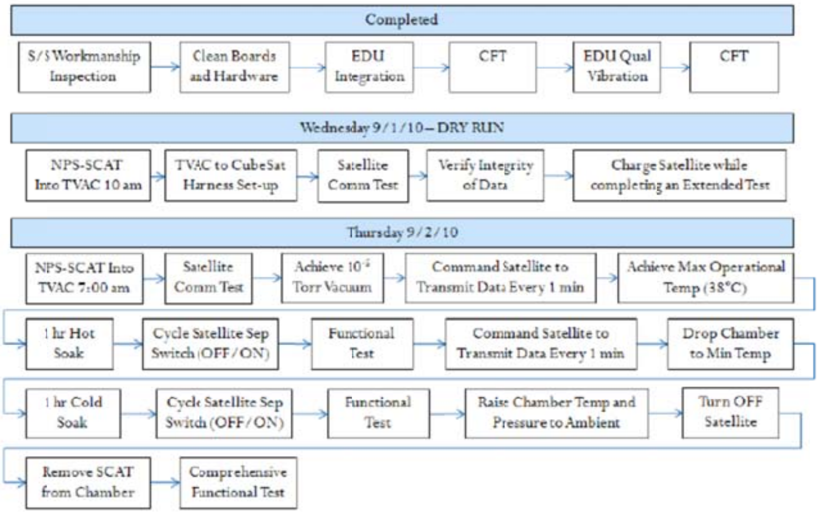

Figure 1: EDU TVAC Testing Task Flow

Naval Postgraduate School		
Date: 9/22/10	Status: Final	Rev: 2.1

2 Safety Information

2.1 Hazards (Example)

Hazards	Remarks	Step Numbers
Use of Toxic or Hazardous Materials	Isopropyl Alcohol	9.2.2
Use of Toxic or Hazardous Materials	Liquid Nitrogen	N/A

2.2 Personnel Protective Equipment

Quantity	Part Number	Equipment
1 pair	NA	Gloves

2.3 Hazard Mitigation

Hazard	Mitigation
Use of Toxic or Flammable Material	Wear glove and goggles

3 Support Requirements

3.1 Personnel Requirements

Quantity	Description
2	Test Operators
1	Quality Control

3.2 External Support Personnel Requirements

Quantity	Description
2	Pre/Post TVAC CFT Personnel
1	Testing Supervisor in SSAG

3.3 Frequency Utilization

MHX 2400 radio broadcasting from TVac to computer at 2.4 GHz.

3.4 Software Requirements

Omega 3 Thermocouple Recording Program

3.5 Other Support

TVAC Support and Liquid Nitrogen Handling – David Rigmaiden

4 Staging Requirements

4.1 Required Documents and Drawings

Document Number	Revision	Description
NA	1.4	NPS-SCAT Comprehensive Functional Test (CFT)

4.2 Referenced Documents and Drawings

Document Number	Revision	Description
GSFC-STD-7000	April 2005	General Environmental Verification Standard (GEVS)
P-POD Mk III ICD	2 August 2007	Poly Picosatellite Orbital Deployer Mk III ICD

4.3 Vehicle Installation Parts

Quantity	Description	Step Number
1	Satellite Radio/TVAC Adapter Cord	9.2.5
1	USB Charging Cord	9.2.7

4.4 GSE and Facility Installation Parts

Quantity	Description	Step Number
1	Delrin Test Stand	9.3.1
1	SCAT TVAC Test Harness	9.2.7

4.5 Tools and Test Equipment

Quantity	Description	Step Number
1	NPS SSL (Tenney Space Jr.) Thermal Vacuum Chamber	Section 9
1	Omega HH147 RS-232 Data Logger Thermometer	9.1.4

5 Requirements Verification

NPS-SCAT KPPs this procedure satisfies:

KPP Number	Description
006	The satellite shall be capable of being launched via a CubeSat standard compatible deployer (like a P-POD) on an Evolved Expendable Launch Vehicle (EELV).

6 Responsibility

6.1 Engineer Responsibilities

The engineer is responsible to:

a. Be present at all times when work is being performed.

b. Verify or provide the document control working copy of this procedure to the work site.

c. Verify or provide a copy of all required documents and drawings listed in section 4.1 to the work site.

d. Verify or provide a copy of all reference documents and drawings listed in section 4.2 to the work site.

e. Give a briefing at the start of each shift.

f. Repeat the briefing if unbriefed technicians are added to the task.

g. Solicit and resolve any questions or problems raised by technicians prior to or in parallel with start of work.

h. Walk down the work area and hardware. Verify ready to support.

i. Observe all work performed and buy each step when that work is complete.

j. Witness and verify recording of cal or cert data for calibrated or load tested items.

k. Witness and verify the setting of test equipment, the reading taken, or torque applied.

6.2 Procedure Redline Changes

The test engineer has redline authority to make real time changes to this procedure. The engineer will sign and date changes, which may include adding new steps and pages. Redline changes to hazardous steps will require concurrence by the Small Satellite Lab manager who may sign and date changes or authorize engineer to record: "Verbal concurrence from the lab manager."

7 Data Recording Requirements

7.1 Special Instructions

Operations containing optional steps (such as verify or install, or perform or not perform) shall be documented manually by drawing a line through the operation not used and drawing a circle around the task performed.

7.2 Data Products

The data product for this procedure is the completed work copy including:

a. All steps bought by the engineer and technician.

b. All steps reviewed by the engineer.

c. The completed procedure bought by the engineer as complete in section 10.1.

Additionally, the following documents are required within 1 week of completing the procedure:

a. A summary of data recorded for the Comprehensive Functional Tests.

b. A test results summary and/or presentation.

If other data formats are used, such as spreadsheets or videos, the data will be stored on the SSAG Sperver in the CubeSat folder.

7.3 Post-Test Data Review

The engineer will place the original, reviewed and signed work copy of the completed procedure in the NPS-SCAT Testing Binder for review and storage per section 11.1.

8 Test Preparations

8.1 Task Prerequisites

Pre-TVAC Comprehensive Functional Test of NPS-SCAT. Review of the CFT by the testing engineers.

8.2 Test Readiness Review

The Test Readiness Review will occur prior to testing and will include the following:

- Test Overview
- Test Objectives
- Testing Personnel
- Equipment and set-up
- Safety and hazard considerations
- Review and concurrence of testing levels
- Testing Timeline

8.3 Pre-task Briefing

The pre-task briefing shall, at a minimum, include the following:

- Personnel assignments
- Required personnel certifications current
- Task Objectives
- Communication discipline
- Unusual performance characteristics
- Operational sequence and critical steps
- Test conduct, observations, and responses
- Test equipment and support material status
- Concurrent activities
- Safety considerations (operational hazards, precautions, emergency actions, and safety apparel)

If a shift change occurs or personnel are added or changed, the briefing shall be repeated.

9 Task Instructions

WARNING

The following steps require the use of Isopropyl Alcohol (DPM 0530) that is flammable and a skin and eye irritant. Personnel shall wear (1) PN: DPM8557 Silver Shield Gloves when handling solvents. Wear (1) PN: DPM13169 Goggles when using this material at eye level or above. Use in well ventilated area.

9.1 Chamber Preparation

9.1.1 Read the Tenney Space Jr. Standard Operating Procedures in Appendix A, including all definitions and descriptions of the chamber.

9.1.2 Procedure Start Time: ______________ Date:______________

9.1.3 Clean the thermal vacuum chamber according to steps 1 and 2 (only) of the "Preconditioning and Calibration" procedures in the Tenney Space Jr. Standard Operating Procedure.

Engineer __________

9.1.4 Thermocouple Set-Up

a. Connect four of the five thermocouples (exiting from the TVAC chamber) to the Omega HH147 RS-232 Data Logger Thermometer. Use the Comm 2 connecter to attach the measurement device to the computer. Turn on the thermometer by holding down the power button then choosing the T type thermocouple. Push the RS232 button to set the thermometer to output to the PC. "PC" and "T" should show up on the screen.

b. On the computer next to the TVAC chamber, open the temperature logging program Omega HH147 on the desktop.

c. The program will open up and you have the option to choose the save interval. Choose the appropriate interval and click enable. The program will automatically begin logging the temperature. The file can be checked by creating a copy and opening it while the program is still logging.

d. Identify each thermocouple, the corresponding number in the Omega_HH147 program, and the location.

Chamber Thermocouple #	#/color in Omega Program	Location/Placement
	T1	
	T2	
	T3	
	T4	

Engineer __________

9.1.5 Locate the coaxial cables for the radio connection to the antenna (located inside the chamber, dropping down from the roof of the chamber). This will be connected to the satellite in section 9.2.

9.2 Test Item Preparation

9.2.1 Put on gloves.

9.2.2 Prepare the test item and test stand by cleaning all surfaces.

Engineer __________

9.2.2 If pictures have not been taken of the test item, do so now.

9.2.3 Place the thermal-vacuum CubeSat testing stand in the chamber.

9.2.4 Place the test item into the thermal vacuum chamber ensuring no wires or protrusions cross the seal. Ensure the tested item does not rest on a wall.

Note

Equipment touching a chamber wall will lead to uneven cooling and heating.

9.2.5 Connect the test item to the radio interface cable and/or testing harness within the chamber. An adapter may be necessary to connect the co-axial cable to the satellite radio.

9.2.6 Connect the thermocouples to the designated measurement points in the chamber and on the CubeSat. Test all connections.

Note

DB50 does not directly correspond to DB 25. DB50 = DB25 + 10. Pins 11-35 on DB50 connect to Pins 1-25 on DB25.

Engineer __________

9.2.7 Connect the harness outside of the TVAC to the measurement and/or control instrumentation.

9.2.8 Connect the antenna to the outside of the thermal vacuum chamber.

For Operational testing:

9.2.9 Turn on computer and/or software necessary to collect and record telemetry.

9.2.10 Turn on the satellite and begin recording telemetry. This will ensure that the satellite can be turned on from outside of the chamber between hot and cold soaks.

9.2.11 Check satellite functionality (eg. Outputs from the temperature sensors match the thermocouples).

Note

For detailed NPS-SCAT testing refer to the EDU TVAC Testing Log.

9.3 Power On Chamber

9.3.1 Before closing the thermal/vacuum chamber verify the CubeSat is in the correct configuration and sitting on the Delrin test stand (Power OFF for workmanship, power ON for operational testing).

9.3.2 Seal the thermal vacuum chamber.

9.3.3 Ensure the seal is clear of all wires, protrusions, dust and any debris.

Caution

Any debris closed in the seal will permanently weaken the seal, diminishing the effectiveness of the thermal vacuum chamber.

9.3.4 Close the door of the thermal vacuum chamber. Check that the small green knob is CLOSED and the large black & white knob is OPEN. Check that the vent is CLOSED.

Note

The outer door has no effect on the pressure of the chamber.

9.3.5 The temperature range* for this test is:

High Temp. ____________________ Duration____________________

Low Temp. ____________________ Duration____________________

*For a detailed NPS-SCAT testing refer to the EDU TVAC Testing Log.

9.3.6 To start the thermal vacuum chamber complete the following procedures:

a. Read the following notes and clarifications before following step b.

i. Safety switch is located on the wall.

ii. Circuit Breakers are located on the front of TVAC.

iii. Mechanical Pump switch is located on the front of TVAC.

1. Turn on the V200 Turbopump immediately after turning on the mechanical pump (box located on top of TVAC, square yellow button). The V200 will automatically start running until the chamber pressure drops below 0.2 Torr on the vacuum gage controller.

iv. The Cold Trap switch is located on the front of the TVAC.

v. If necessary for test, see Mr. David Rigmaiden for instructions regarding absolute altitude (using liquid nitrogen).

vi. You can select the desired temperature using the set-point gage located on the front of TVAC. Push and turn to temperature, release. Do Not change the temperature yet.

b. Follow the procedures listed under "Making a Space Run" in the Tenney Space Jr. Standard Operating Procedure (SOP), located in Appendix A of this document. Refer to the notes above while following the procedure.

As of this revision, the most current version of the Tenney Space Jr. SOP is dated 3-29-2010. Mr. David Rigmaiden can provide the most current version of the procedure.

Engineer __________

9.4 Heating the Thermal Vacuum Chamber

9.4.1 When the pressure on the ion gauge drops to 10^-5 Torr the heat in the thermal vacuum chamber can be increased.

9.4.2 Complete the following procedures:

a. Turn on the Door Heat (front of TVAC).

b. Turn on Heat (front of TVAC).

c. Monitor the thermocouples for any dramatic/unexpected increases.

Engineer __________

9.4.3 Continue to adjust the set point to reach the desired temperature. To reach the hot soak temperature, the set point will need to be set above the desired temperature.

Note

The temperature set at the display reads the temperature of the chamber wall which is slightly different than the temperature inside the chamber. The temperature inside the chamber can be monitored by using the thermocouples placed in the chamber. All temperature readings are in Celsius.

9.4.4 When the thermal vacuum chamber reaches the desired temperature, note the time and begin a hot soak in accordance with your testing profile.

Start Time of Hot Soak ____________ End Time________________

Engineer __________

9.4.5 If required during Operational testing, complete a functionality test at high temperature.

9.4.6 Cool the thermal vacuum chamber to ambient temperature according to section 9.5.

9.5 Cooling the Thermal Vacuum Chamber

9.5.1 Complete the following procedures in accordance with the functionality outlined in the Tenney Space Jr. Standard Operating Procedure:

a. Turn OFF all heating elements (HEAT and DOOR HEAT).

b. If using liquid nitrogen (LN_2), turn ON both handles on the liquid nitrogen tank.

c. Turn Ambient Cooling (front of TVAC) ON when cooling down to 0°C.

d. If stopping at ambient temperature, (approx. 22°C), record the time and (avg.) temperature.

Time______________ Temp. ________________

Engineer __________

e. After recording the time, continue using Ambient Cooling to decrease the chamber temperature.

f. At 0°C, turn OFF Ambient Cooling.

Caution

Using both AMBIENT COOLING and SUB-ZERO COOLING will freeze the lines within the thermal vacuum chamber.

Engineer __________

g. Turn Sub-zero Cooling (front of TVAC) ON from 0°C and below.

h. Monitor the thermocouples to verify expected cooling.

Engineer __________

9.5.2 Adjust the set point to desired temperature. To adjust the temperature down push the knob in, twist to the left and release to set.

Note

The temperature set at the display reads the temperature of the chamber wall which is slightly different than the temperature inside the chamber. The temperature inside the chamber can be monitored by looking at the Wahl Thermocouple display on top of the thermal vacuum chamber. There are up to five thermocouples to choose from. All temperature readings are in Celsius.

9.5.3 When the thermal vacuum chamber reaches the desired temperature, note the time and begin the cold soak duration in accordance with your testing profile.

Start of cold soak ____________ End Time_______________

Engineer _________

9.5.4 If required during Operational testing, complete a functionality test at high temperature.

9.6 Return to Ambient Temperature from Cold Soak

9.6.1 Complete the following procedures in accordance with the functionality outlined in the Tenney Space Jr. Standard Operating Procedure:

a. If using liquid nitrogen (LN_2), turn Off both handles on the liquid nitrogen tank.

b. Turn on the HEATER and DOOR HEATER.

c. Adjust the set-point slightly above ambient temperature.

d. Turn off the HEATERs as the chamber approaches ambient temperature.

e. Note the time when the satellite reaches ambient temperature (approx. 22°C).

Time ____________ Temp____________

Engineer _________

f. Complete a functional test if required during Operational testing.

9.7 Return Chamber to Ambient Pressure

9.7.1 Bring the thermal vacuum chamber temperature above ambient temperature (approx. 25°C).

9.7.2 Follow the instructions for "Returning to Site Altitude" in the Tenney Space Jr. Standard Operating Procedure (SOP) in Appendix A. Read the following notes to clarify procedures listed in the SOP.

a. The COLD TRAP switch is located on the front of the chamber.

b. To turn off the liquid nitrogen, close both handles on the tank.

c. The Turbo V200 pump is located above the chamber.

d. WAIT until the noise of the V200 winding down has been heard.

e. Ensure the chamber is above ambient temperature, then open the vent (front of chamber, many turns to open) and allow the gaseous nitrogen (valve on tank, half turn to open) to bleed dry nitrogen into the chamber. The pressure will begin to rise inside the chamber.

f. Listen for the Mechanical Pump to make a gurgling noise, then turn OFF the Mechanical Pump switch (front of chamber). The chamber should be at approx. 1.0 +2 Torr.

NOTE

Do not allow the pressure to increase above 760 TORR. Shut off the gas and close vent at this pressure. Failure to follow these procedures could result in damage to the chamber.

g. CLOSELY monitor the chamber pressure as soon as you turn off the Mechanical Pump. When the chamber pressure reaches ambient (approx. 7.6 +2 Torr) immediately turn OFF the gaseous nitrogen valve (on tank, approx. half turn). Then close the Vent (front of chamber).

Engineer __________

9.8 Turning off the TVAC

9.8.1 Turn off the Breaker on the front of the chamber.

9.8.2 Close the safety switch on the wall.

9.8.3 Allow the chamber to cool to room temperature (approx. 22 C) before opening the chamber. (No action necessary, wait approx. 15 minutes)

Engineer __________

9.9 Remove Test Item from Chamber

9.9.1 Be cautious in handling the satellite in case of retained heat.

9.9.2 Remove the satellite from the chamber and return to workbench or clean room.

Procedure End Time/Date ____________________________

Name ________________________ Sig. ________________

Name ________________________ Sig. ________________

10 Facility Emergency Procedures

This appendix establishes the emergency procedures for the facility should major conditions occur which could lead to possible fire or danger.

ACTIVITY	PHONE NUMBER
Lab Manager, David Rigmaiden	(831) 236-5206
Vibration Table Supervisor, Dan Sakoda	(831) 917-1763
Professor, Dr. James Newman	(831) 392-5789
Fire Department	9-911 (on campus)

If an emergency evacuation is necessary while tests, assembly or handling operations are in progress, the responsible individual will make his/her equipment safe, if conditions permit it, before evacuating the area.

NOTE

Under no circumstances will personnel attempt emergency procedures other than shutdown and evacuation. Personnel will take specific instruction from the Engineer or designee prior to re-entry while the emergency still exists.

Personnel who are affected by the emergency situation will evacuate by the most direct route available and proceed to the assigned Emergency Evacuation Assembly Point (EEAP).

Personnel shall notify the supervisor/test engineer of their safe evacuation and await further instructions.

EMERGENCY SUMMARY

a. Call 9-911
b. Shut-down or render systems safe, if conditions permit
c. Locate CO2 fire extinguisher
d. Evacuate personnel from lab if necessary
e. Notify Lab Manager and await further instructions

11 Task Completion Review

11.1 Engineer Review of Procedure Task Completion

The signature below indicates that the undersigned engineer has reviewed the completed work copy of this procedure, and the hardware affected, and is satisfied that the work is correct and complete.

____

Engineer Signature Date

____

Engineer Printed Name

Appendix A

Tenney Space Jr.

Standard Operating Procedure

Mains Safety Switch

Safety switch on wall provides main power to the chamber. The switch must be in the off position for servicing and maintenance.

The Circuit Breakers

The breakers are shown schematically on drawing E-1758-3. They perform the following functions:

1CB, 5 pole, energizes the thermal control circuits with 230 volt power through poles 2 and 3. It also energizes the condenser fan and refrigeration compressors through poles 4 and 5. You must close this breaker in order to operate the chamber with heat or cooling or to use the cold trop.

Functions of the Manual Switches

The switches are shown schematically on drawing E-1758-3, and perform the following functions:

1SS Heat switch places the shell heaters under command of the TempTenn temperature controller through high heat cutout 1TS. This switch also arms the door heat switch; consequently you may not operate door heat unless the shell heaters are also operating. Close the heat switch whenever you want to operate the chamber over ambient.

2SS Ambient Cooling switch energizes the refrigeration system (both compressors and the condenser fan). This switch selection opens solenoid valve SV1, directing cold gas through the cooling coils rather than liquid. Thus, refrigeration capacity is reduced and TempTenn can control moderate temperatures more smoothly than with subzero cooling. Also, when the shell is very hot and you want to cool it, you may want to use ambient cooling for the start of your pulldown simply because doing so is easier on the refrigeration system. However, if you want to make a rapid pulldown with subzero cooling, there's no law against doing so.

3SS Subzero Cooling (do run together with 2SS Ambient Cooling) switch energizes the refrigeration system. It also opens solenoid valve SV2 which feeds liquid refrigerant to the cooling coils for maximum cooling capacity. Close this switch when you want to simulate lowest temperatures or when you want fastest pulldown. In either case, refrigeration is modulated by TempTenn's command of artificial loading valve SV3.

4SS Mechanical Pump switch energizes the mechanical vacuum pump.

6SS Cold Trap witch energizes the refrigeration system and opens liquid line solenoid valve SV4. The valve feeds liquid refrigerant to the chamber cold trap.

Note: Turn the cold trap on only when you have roughed the chamber down to about 100 microns. If you chill the trap at higher pressures, it may become contaminated by moisture.

7SS Door Heat switch is armed only when the HEAT switch is closed. Closing of the door heat switch places the door heater under command of the TempTenn temperature controller.

1PB Reset push button restores heat to the shell heaters and resets the high heat cutout when temperature returns to within acceptable limits. If you press this button while temperature is still too high, heat will not be restored.

What The Pilot Lights Indicate

This describes what is indicated as each light glows:

1LT Heat: the 1,250 watt shell heater is energized. When this light cycles on and off regularly, the shell is at or close to temperature setpoint.

2LT Ambient Cooling: The refrigeration system is running, directing cold gas to the cooling coils.

3LT Subzero Cooling: The refrigeration system is running, directing liquid refrigerant to the cooling coils.

4LT Mechanical Pump: The mechanical vacuum pump is running.

6LT Cold Trap: The refrigeration system is running, and liquid is directed to the cold trap.

7LT Door Heat: The door heater is energized.

Selecting Temperature on TempTenn

To select temperature setpoint, simply press in on the selector knob and rotate it until your desired temperature appears in the display window. Then release the knob. When the knob is released, the display will be actual shell temperature.

High Heat Cutout 1TAS

This chamber has a 340 electronic heat cutout shown as 1TS on the electrical drawings. Upon detecting shell temperature above its setpoint, the cutout disables the heater. It does so by opening the circuit from the heat switch to the heater.

Preconditioning and Calibration

Before running a space test program, clean, precondition and calibrate the space chamber as follows:

1. Turn off Safety Switch
2. Physically clean the chamber by brush or HEPA vacuum cleaner. Wash the interior with water and mild detergent to remove grease and oils if necessary. Dry with lintless cloth. Rinse with distilled water. Dry with clean lintless cloth. A 50/50

mixture of distilled water and 99% Isopropyl Alcohol may be used. Dry with lintless cloth. (Avoid cleaning with acetone or strong solvent that will damage black paint inside the chamber.)

3. Take the chamber to high altitude as described under "Making a Space Run." Follow steps 1 through 8.
4. Bring up the heat, bit by bit using the temperature controller.
5. Increase temperature till you reach maximum. Hold this temperature until chamber pressure levels off and remains steady for several hours.
6. Calibrate the vacuum instrument as described in the Granville Phillips manual. **(PERFORM ONLY IF TEST PLAN REQUIRES IT)**
7. Carefully vent the chamber as described under "Returning to Site Altitude."
8. Bleed in clean, dry GN2 until the mechanical pump gurgles. Then shut down the mechanical pump and complete the venting.
9. Don't open the chamber door until you're ready to insert the test specimen. Open and close door as quickly as possible when loading the chamber. Keep it spotless.

Making a Space Run – Turn off Safety Switch

1. Inspect door, penetrations and ionizations gauge glass tube for tightness.
2. Turn on Safety Switch
3. Close the circuit breakers.
4. Turn on the mechanical pump.
5. Pump the chamber with the mechanical vacuum pump until pressure falls to 200 microns or less as indicated on chamber thermocouple gauge.
6. Turn on the Turbo V200 turbo pump controller.
7. Turn on the cold trap.
8. If you want absolute ultimate altitude, feed liquid nitrogen to the cold trap and shut off the cold trap switch.
9. Select desired temperature on TempTenn.

Returning to site Altitude

1. Shut off the cold trap switch or turn off liquid nitrogen if it is being used.
2. Turn off Turbo U200 pump. (Keep the mechanical pump running.)
3. Allow Turbo U200 to stop. Do not stop the mechanical pump yet.
4. If the shell is colder than ambient, warm it a little above ambient.
5. Bleed in clean gaseous nitrogen until the mechanical pump gurgles. Finally, shut down the mechanical pump.

Part Identification

Component parts are shown and identified on the drawings accompanying the chamber.

DANGER

THE MACHINERY COMPARTMENT HAS EXPOSED ELECTRICAL CONNECTIONS.

CAUTION

THIS IS NOT AN EXPLOSION-PROOF CHAMBER. DO NOT TEST ANY PRODUCT IN THE CHAMBER WHICH IS CAPABLE OF GENERATING COMBUSTIBLE MIXTURES.

WARNING

DISCONNECT ALL ELECTRICAL POWER FROM THE CHAMBER BEFORE SERVICING OR CLEANING THE MACHINERY COMPARTMENT. ANY OPERATION NOT ADDRESSED IN THIS DOCUMENT MUST NOT BE PERFORMED WITHOUT PRIOR WRITTEN APPROVAL.

APPENDIX C. TVAC TEST LOG

Time	Time Elapsed	Test Progress/Description	IG	Chamber Pressure (Torr)	Foreline Pressure (Torr)	Temp on Front of Chamber Door, deg C	T1	T2	T3	T4	SCAT Panel (+X)	SCAT Panel (+Z)	SCAT Panel (-Y)	Sun Sensor Temp	Battery Voltage	Battery Temp*	*Annotated the hotter of Battery 0 and Battery 1
7:55	0:00	Turned on Chamber		7.60E+02		24.00											
8:00	0:05	Mechanical Pump on		1.70E+02		22.00	20.50	24.00	6.90	23.50				26.20	8.26		
8:12	0:17	V200 came ON		6.50E-03		16.30	19.50	22.50	21.00	22.60				26.20	8.26	23.00	
8:25	0:30			5.80E-03	1.80E-01	10.70	18.10	18.50	19.10	22.00				26.20	8.26	23.30	
8:33	0:38		2.60E-04	3.90E-03	2.50E-01	7.60	16.70	17.00	26.60	21.40				26.60	8.27	24.00	
8:43	0:48		1.60E-04	1.60E-03	1.10E-01	33.50	25.90	21.70	52.20	24.70				26.40	8.27	24.30	
8:50	0:55		2.20E-04	3.00E-03	1.70E-01	25.40	27.30	22.30	38.10	25.60				27.00	8.27	24.60	
8:55	1:00	Heat ON, Door Heat ON, Set point: 60C	1.00E-04	1.60E-03	9.00E-02	21.10	26.50	21.80	33.10	25.80				27.30	8.27	25.30	
9:00	1:05		3.70E-05	1.10E-03	5.40E-02	26.60	26.60	22.70	69.70	26.30				28.00	8.27	25.60	
9:05	1:10	Set Point changed to 38C	4.10E-05	1.00E-03	5.80E-02	55.00	36.90	29.60	104.70	30.30	32.10			28.70	8.27	25.90	SCAT Panel measured is +X (hottest of the 6 panels)
9:10	1:15	Turned off Door Heat and Heat	4.30E-05	1.00E-03	5.80E-02	65.40	44.80	33.10	85.50	33.10	35.70			29.30	8.27	26.60	
9:12	1:17	HOT SOAK Begins	4.50E-05	1.00E-03	5.90E-02	60.00	46.50	34.00	73.30	34.50	38.20			30.00	8.27	27.40	
9:14	1:19	Heat ON, Door Heat ON, Set point: 30C															
9:18	1:23	Set Point changed to 35C	4.50E-05	1.00E-03	5.70E-02	49.20	48.10	34.00	60.30	35.50	39.70			31.40	8.27	28.20	
9:21	1:26	Door heat ON, Set Point 40C															
9:25	1:30	Set Point 45C	4.10E-05	9.00E-04	5.30E-02	39.50	45.10	32.80	52.00	35.40	40.00			33.60	8.27	30.20	
9:31	1:36	Set Point 40C	4.00E-05	1.10E-03	5.30E-02	48.90	46.30	34.30	75.10	36.60	40.40			34.50	8.27	31.20	
9:37	1:42		3.90E-05	1.10E-03	5.30E-02	48.80	48.20	35.10	49.70	37.50	41.70			35.90	8.27	32.10	
9:45	1:50		3.90E-05	9.00E-04	5.00E-02	40.10	46.40	34.40	38.70	37.60	42.20			37.70	8.27	34.10	
9:47	1:52	Set Point 45C															
9:53	1:58	Set Point 42C	3.70E-05	9.00E-04	4.90E-02	46.70	46.20	35.30	68.10	38.50	42.10			39.00	8.27	35.40	
10:00	2:05		3.70E-05	9.00E-04	4.90E-02	47.50	49.30	36.90	48.80	40.10	44.40			40.90	8.27	37.00	
10:06	2:11		3.60E-05	9.00E-04	4.80E-02	41.00	47.90	36.20	42.00	40.20	44.60			41.70	8.27	37.70	
10:12	2:17	End HOT SOAK	3.50E-05	9.00E-04	4.60E-02	41.40	47.00	36.20	53.50	40.20	44.40			42.40	8.28	38.50	Unplugged the charger and opened Sep switch
		Functional Test after 1 Hr Hot Soak															
10:17	2:22	Heat OFF, Door Heat OFF, Set point: -40C	3.50E-05	9.00E-04	4.60E-02	44.00	48.20	36.80	47.20	40.90	45.10			34.40	8.26	40.00	
		Ambient Cooling ON															Started 1 min loop again
10:24	2:29		3.70E-05	9.00E-04	4.90E-02	36.20	36.20	33.00	26.90	40.00	44.50			44.20	8.26	40.30	
10:31	2:36		3.30E-05	9.00E-04	4.60E-02	27.50	25.20	28.30	10.70	38.20	40.60			44.90	8.27	41.60	
10:40	2:45		2.50E-05	9.00E-04	3.60E-02	18.90	16.10	23.90	-4.10	35.80	36.40			44.70	8.28	41.60	
10:50	2:55		3.20E-05	8.00E-04	3.20E-02	11.70	9.90	20.10	6.40	33.00	32.60			43.40	8.28	41.30	

Time	Time Elapsed	Test Progress/Description	IG	Chamber Pressure (Torr)	Foreline Pressure (Torr)	Temp on Front of Chamber Door, deg C	T1	T2	T3	T4	SCAT Panel (+X)	SCAT Panel (+Z)	SCAT Panel (-Y)	Sun Sensor Temp	Battery Voltage	Battery Temp*	*Annotated the hotter of Battery0 and Battery 1
11:00	3:05		2.70E-05	8.00E-04	2.70E-02	6.00	6.00	17.30	3.30	30.30	29.00			41.70	8.28	39.80	
11:10	3:15		2.40E-05	8.00E-04	2.40E-02	2.70	4.00	15.50	1.90	28.20	26.70			40.00	8.28	38.30	
11:20	3:25	Ambient Cooling OFF, Sub-Zero Cooling ON	1.90E-05	7.00E-04	2.10E-02	0.00	0.60	13.80	0.80	26.20	24.70			38.10	8.28	36.70	
11:30	3:35		1.50E-05	7.00E-04	1.90E-02	-4.40	-0.20	8.70		22.50		13.70		35.60	8.28	34.60	SCAT Panel measured is +Z (coldest of the 6 panels)
11:40	3:45		1.20E-05	7.00E-04	1.60E-02	-25.60	-1.10	4.30		18.80		8.50		32.70	8.28	32.10	
11:50	3:55	Set Point -60C	1.00E-05	7.00E-04	1.40E-02	-45.20	-3.20	0.30		15.40		4.80		30.00	8.27	29.90	
12:00	4:05		8.40E-06	7.00E-04	1.30E-02	-53.00	-8.60	-2.80		12.30			-4.30	27.00	8.25	27.40	SCAT Panel measured is the -Y (coldest of the 6 panels)
12:10	4:15		7.00E-06	7.00E-04	1.20E-02	-60.60	-11.90	-5.70		9.40			-8.20	23.70	8.27	24.10	
12:20	4:25	Set Point -80C	5.90E-06	7.00E-04	1.10E-02	-64.00	-21.60	-8.40		6.40			-11.60	20.50	8.27	21.40	
12:30	4:35		5.10E-06	7.00E-04	1.00E-02	-66.00	-36.20	-10.60		4.20			-14.10	17.60	8.27	18.80	
12:40	4:45	Unplugged the charging cable	4.40E-06	7.00E-04	1.00E-02	-67.70	-41.20	-12.70		1.50			-16.60	14.00	8.27	15.50	
12:50	4:55		3.60E-06	7.00E-04	9.80E-03	-68.90	-45.00	-14.40		-0.60			-18.60	11.50	8.19	12.90	
13:00	5:05		3.30E-06	7.00E+04	9.40E-03	-69.80	-50.40	-16.20		-2.90			-20.90	8.30	8.14	9.30	
13:10	5:15		2.90E-06	6.00E-04	9.10E-03	-70.70	-66.90	-18.00		-5.20			-23.10	4.40	8.10	5.70	
13:20	5:25		2.70E-06	7.00E-04	8.90E-03	-71.20	-88.90	-19.40		-7.00			-24.80	2.20	8.06	3.10	
13:30	5:35		2.50E-06	7.00E-04	8.70E-03	-71.70		-20.50		-8.90			-26.60	-0.70	8.02	0.50	
13:40	5:45	Begin COLDSOAK	2.30E-06	8.00E-04	8.50E-03	-72.20		-22.00		-10.60			-28.40	-4.20	7.95	-2.30	
		Charging cable plugged back in															
13:50	5:55		2.10E-06	6.00E-04	8.40E-03	-72.40		-23.10		-12.10			-29.00	-6.00	8.04	-4.20	
14:00	6:05		2.10E-06	7.00E-04	8.30E-03	-72.60		-23.90		-13.20			-30.40	-7.80	8.04	-5.40	
14:10	6:15	Unplugged the charging cable	2.00E-06	7.00E-04	8.30E-03	-73.00		-25.00		-14.30			-31.20	-10.00	8.06	-6.30	
14:18	6:23	Set Point -30C, Sub-zero Cooling OFF	1.90E-06	7.00E-04	8.20E-03	-73.40		-25.60		-15.30			-32.20	-11.00	7.83	-4.70	
14:25	6:30		1.90E-06	7.00E-04	8.20E-03	-73.70		-26.10		-15.90			-32.90	-12.10	7.74	-5.00	
14:30	6:35		1.90E-06	7.00E-04	8.40E-03	-71.70		-26.40		-16.30			-33.30	-13.00	7.69	-6.70	
14:37	6:42		1.90E-06	6.00E-04	8.40E-03	-69.20		-26.50		-16.60			-33.50	-14.60	7.71	-7.10	
14:40	6:45	End COLD SOAK															
		Functional Test after 1 Hr Cold Soak															
14:43	6:48	Heat ON, Door Heat ON, Set Point 24C	1.90E-06	7.00E-04	8.20E-03	-66.90		-26.40		-16.90			-33.40	-15.00	7.66	-6.80	
14:50	6:55		2.90E-06	7.00E-04	9.00E-03	-37.40		-22.20		-14.90			-31.90	-15.70	7.63	-4.40	
14:58	7:03		2.80E-06	7.00E-04	8.80E-03	18.00		-8.80		-7.30			-21.00	-16.10	7.61	-5.50	Note: -Y is no longer the coldest panel...but still reading -Y
15:05	7:10		2.70E-06	7.00E-04	9.00E-03	24.30	-51.30	-0.40	40.50	-0.30			-8.60	-15.30	7.60	-6.60	
15:20	7:25		3.60E-06	7.20E-04	9.80E-03	23.90	-16.90	6.60	37.90	5.70			3.60	-10.30	7.57	-7.10	
15:28	7:33		4.10E-06	7.00E-04	1.00E-02	24.90	-11.20	8.70	52.40	7.70			6.20	-7.10	7.57	-4.90	
15:35	7:40	Heat OFF, Door Heat OFF	4.50E-06	7.00E-04	1.00E-02	24.80	-4.80	10.30	33.50	9.70			9.00	-4.60	7.57	-4.20	
15:45	7:50		4.80E-06	7.00E-04	1.00E-02	14.90	-2.80	9.80	20.10	10.40			9.30	-1.70	7.56	-2.90	
15:53	7:58	Heat ON, Door Heat ON	5.00E-06	7.00E-04	1.10E-02	9.20	-6.20	9.10	15.90	10.20			8.60	0.10	7.57	-1.40	
16:00	8:05	Charging cable plugged back in	5.70E-06	7.00E-04	1.10E-02	29.60	-1.60	12.60	65.90	12.50			10.50	2.20	7.57	0.20	
16:10	8:15		6.70E-06	7.00E-04	1.20E-02	27.10	30.80	15.50	35.20	15.90			16.10	4.50	7.69	3.10	
16:20	8:25		7.20E-06	7.00E-04	1.20E-02	22.80	29.20	15.90	43.60	17.00			16.60	8.30	7.73	6.20	
16:30	8:35		8.10E-06	8.00E-04	1.30E-02	22.60	30.30	16.90	31.70	18.40			18.60	11.40	7.75	9.00	
16:40	8:45		8.70E-06	8.00E-04	1.20E-02	26.30	30.90	18.20	40.70	20.10			19.60	14.00	7.76	11.60	
16:45	8:50	Set Point: 30C	9.20E-06	8.00E-04	1.40E-02	21.80	30.80	18.40	32.50	20.90			20.40	15.80	7.78	13.70	
16:50	8:55		9.70E-06	8.00E-04	1.40E-02	31.60	31.70	20.20	68.00	22.20			21.60	17.30	7.79	15.20	
16:55	9:00	Heat OFF, Door Heat OFF, Set point: 23C	1.00E-05	7.00E-04	1.50E-02	39.20	18.90	22.10	59.10	23.60			23.90	18.00	7.79	15.50	
17:00	9:05	Cold Trap Off															
17:05	9:10	MAIN POWER OFF	1.40E-05	8.00E-04	1.50E-02	29.90							26.20	20.50	7.80	18.00	
17:16	9:21	LAST READING, Ambient Pressure	-	7.30E+02	7.70E+02	24.00	22.10	24.00	30.30	23.50			24.60	24.10	7.82	21.40	

APPENDIX D. SCAT MATERIAL AND PHYSICAL PROPERTIES

Node	Description	Material	Source*	ρ Density [kg/m³]	Source*	k Thermal Cond. [W/m-K]	Source*	Cp Specific Heat [J/kg-K]	Source*	α Absorptivity	Source*	ε Emissivity	Source*	Thickness [mm]	Thickness Name	FEM Mesh Color
1	Structure +Y side	Aluminum 5052-H32 (anodized)	1	2680	2	138	2	880 963	2 6	0.31	23	0.8	23	1.2	Chassis	White
2	Structure Top	Aluminum 5052-H32 (anodized)	1	2680	2	138	2	880	2	0.31	23	0.8	23	1.2	Chassis	White
3	Structure Bottom	Aluminum 5052-H32 (anodized)	1	2680	2	138	2	880	2	0.31	23	0.8	23	1.2	Chassis	White
4	Solar PCB +Z	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
		TASC(GaInP2/GaAs/Ge)	8	5317	12	55**	10	330**	10	0.92	7	0.85	7	0.4	Solar Cell	Dark Green
		ITJ ($GaInP_2$/GaAs/Ge)	7	5317	12	55**	10	330**	10	0.92	7	0.85	7	0.4	Solar Cell	Dark Green
		BTJM (InGaP/InGaAs/Ge)	9	5500	11	5	11	300	11	0.92	7(1)	0.85	7(1)	0.4	Solar Cell	Dark Olive
		Polycrystalline Silicon		2329	14	130	13	700	13	0.92	7(1)	0.85	7(1)	0.4	Solar Cell	Light Blue
5	Solar PCB -Z	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
		TASC		5317	12	55	10	330	10	0.92	7	0.85	7	0.4	Solar Cell	Dark Green
6	Solar PCB +Y	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
		TASC		5317	12	55	10	330	10	0.92	7	0.85	7	0.4	Solar Cell	Dark Green
7	Solar PCB -X	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
		ITJ		5317	12	55	10	330	10	0.92	7	0.85	7	0.4	Solar Cell	Dark Green
8	Solar PCB -Y	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
		ITJ		5317	12	55	10	330	10	0.92	7	0.85	7	0.4	Solar Cell	Dark Green
9	Solar PCB +X	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
		ITJ		5317	12	55	10	330	10	0.92	7	0.85	7	0.4	Solar Cell	Dark Green
10	Patch Antenna	Ceramic (96% Alumina or Al_2O_3)	15	3709	16	25	17	880	17	0.55	24	0.8	28	2.5267025	Patch Ant Substrate	White
		Silver		10510	6	418	6	230	6	0.18	20(1)	0.06	19	0.1	Patch Ant Conductor	Gray
11	FM430	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Light Blue
12	MHX 2400 Radio	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.8	MHX	Magenta
13	EPS	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
14a	Battery PCB Board	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Gray (RGB 505050)
14b	Batteries	Lithium Polymer (alum foil casing)	25	2701	26	235	27	921	26	0.15	20	0.05	20	0.100	Battery	Yellow
15	Beacon Board	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
16	Payload (SMS)	FR-4		1850	3	0.23	4	1200	4	0.85	18	0.85	18	1.575	PCB	Green
17	Sun Sensor	Gold	29	18900	6	318	6	130	6	0.09	20(1)	0.03	19	same	same	Golden Orange
		Aluminum 6061-T6	29	2710	6	167	6	1256	6	0.31	23	0.8	23	3.843	Sun Sensor	
		Synthetic Sapphire Crystal	29	4000	5	25.12	5	418	5	0.7	21	0.9	21	same	same	Blue
18	Structure -X side	Aluminum 5052-H32 (anodized)	1	2680	2	138	2	880	2	0.31	23	0.8	23	1.2	Chassis	White
19	Structure -Y side	Aluminum 5052-H32 (anodized)	1	2680	2	138	2	880	2	0.31	23	0.8	23	1.2	Chassis	White
20	Structure +X side	Aluminum 5052-H32 (anodized)	1	2680	2	138	2	880	2	0.31	23	0.8	23	1.2	Chassis	White
TOTAL = 21 nodes																

Sources listed by number:

1	http://www.cubesatkit.com/content/faq.html
2	http://www.glemco.com/pdf/NEW_MARTERIAL_LIST/Aluminum%205052-H32.pdf
3	http://www.plasticsintl.com/datasheets/Phenolic_G10_FR4.pdf
4	http://www.frigprim.com/online/cond_pcb.html
5	http://www.stanfordmaterials.com/synthetic-sapphire.html
6	http://www.engineersedge.com/properties_of_metals.htm
7	http://www.spectrolab.com/DataSheets/TNJCell/tnj.pdf
8	http://www.spectrolab.com/DataSheets/PV/PV_NM_TASC_ITJ.pdf
9	http://www.emcore.com/assets/photovoltaics/Emcore+BTJM+Solar+Cell+Data+Sheet_May-07.pdf
10	http://www.ioffe.ru/SVA/NSM/Semicond/GaAs/thermal.html
11	http://www.ioffe.ru/SVA/NSM/Semicond/GaInAs/thermal.html
12	http://www.ioffe.ru/SVA/NSM/Semicond/GaAs/mechanic.html
13	http://www.ioffe.ru/SVA/NSM/Semicond/Si/thermal.html
14	http://www.ioffe.ru/SVA/NSM/Semicond/Si/mechanic.html
15	Matt Schroer's Thesis \\xsperver.ern.nps.edu\cubesat\Student Theses\Thesis - Schroer
16	http://www.specemc.com/structural.asp
17	http://accuratus.com/alumox.html
18	http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04432819
19	http://www.monarchserver.com/TableofEmissivity.pdf
20	http://www.solarmirror.com/fom/fom-serve/cache/43.html
21	Doug Sinclair - his educated guess from a telephone conversation with him on 1/12/2011
22	http://web.byv.kth.se/bphys/pdf/art_0103.pdf
23	Spacecraft Thermal Control Handbook, Vol. 1 Edited by David Gilmore. Appendix A, pg 799
24	No source. Used 0.55 since I couldn't find anything out.
25	www.clyde-space.com/documents/1496
26	http://www.aluminumfoils.com/blog/?page_id=34
27	http://www.alufoil.org/upload/media/Alufoil_File_2.pdf
28	http://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html
29	http://www.sinclairinterplanetary.com/digitalsunsensors
** Germanium Specific Heat is 310 and Thermal Conductivity is 58.	

APPENDIX E. CONDUCTION MATRICES

Description	Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14a	14b	15	16	17	18	19	20
Structure +Y side	1	0	A,E	B,E	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	D	0	D
Structure Top	2	A,E	0	0	C	0	E	E	E	E	0	0	0	0	0	0	0	0	0	A	A	A
Structure Bottom	3	B,E	0	0	0	C	E	E	E	E	F	FF,Q	0	0	0	0	0	0	0	A	A	A
Solar PCB +Z	4	0	C	0	0	0	E	E	E	E	0	0	0	0	0	0	0	H	0	0	0	0
Solar PCB -Z	5	0	0	C	0	0	E	E	E	E	0	0	0	0	0	0	0	J	0	0	0	0
Solar PCB +Y	6	0	E	E	E	E	0	E	0	E	0	0	0	0	0	0	K,V	J	0	0	0	0
Solar PCB -X	7	0	E	E	E	E	E	0	E	0	0	0	0	0	0	0	0	J	0	0	0	0
Solar PCB -Y	8	0	E	E	E	E	0	E	0	E	0	0	0	0	0	0	0	J	0	0	0	0
Solar PCB +X	9	0	E	E	E	E	E	0	E	0	0	0	0	0	0	0	0	J	0	0	0	0
Patch Antenna	10	0	0	F	0	0	0	0	0	0	0	0	L	0	0	0	0	0	0	0	0	0
FM430	11	0	0	FF,Q	0	0	0	0	0	0	0	0	M,N	G,P1,X1	0	0	0	0	0	BB	0	BB
MHX 2400 Radio	12	0	0	0	0	0	0	0	0	0	L	M,N	0	0	0	0	0	0	0	0	0	0
EPS	13	0	0	0	0	0	0	0	0	0	0	G,P1,X1	0	0	R,S	0	P2,X2	T	0	0	0	0
Battery PCB Board	14a	0	0	0	0	0	0	0	0	0	0	0	0	R,S	0	U	0	0	0	0	0	0
Batteries	14b	0	0	0	0	0	0	0	0	0	0	0	0	0	U	0	0	0	0	0	0	0
Beacon Board	15	0	0	0	0	0	K,V	0	0	0	0	0	0	P2,X2	0	0	0	P3,X3	0	0	0	0
Payload (SMS)	16	0	0	0	H	J	J	J	J	J	0	0	0	T	0	0	P3,X3	0	W,Y	Z,X4	0	Z,X4
Sun Sensor	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	W,Y	0	0	0	0
Structure -X side	18	D	A	A	0	0	0	0	0	0	0	BB	0	0	0	0	0	Z,X4	0	0	D	0
Structure -Y side	19	0	A	A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	D	0	D
Structure +X side	20	D	A	A	0	0	0	0	0	0	0	BB	0	0	0	0	0	Z,X4	0	0	D	0

Figure 54 SCAT Conduction Matrix

Description	Node	4	5	6	7	8	9
Solar Cells +Z	N/A	CC,EE	0	0	0	0	0
Solar Cells -Z	N/A	0	DD	0	0	0	0
Solar Cells +Y	N/A	0	0	DD	0	0	0
Solar Cells -X	N/A	0	0	0	AA	0	0
Solar Cells -Y	N/A	0	0	0	0	AA	0
Solar Cells +X	N/A	0	0	0	0	0	AA

Figure 55 Solar Cell Conduction Matrix

A	**1 screw (Chassis Screw)**
B	**3 screws (Chassis Screw)**
C	4 clips (anodized 6061-T6 Aluminum) - **IGNORE**
D	Connected via the structure (1 piece of metal) - **IGNORE**
E	2 clips (anodized 6061-T6 Aluminum) - **IGNORE**
F	**Built in 3M adhesive on the patch antenna**
G	**4 Hex stud stand-offs (tops only)**
H	Samtec 16 pin connector + ends -**IGNORE**
	Samtec 16 pin ribbon cable (4 in) (d_wire = .254 mm)
	Samtec 16 pin connector ends (2 of them) (d = .4mm)
J	Samtec 10 pin connector + ends -**IGNORE**
	Samtec 10 pin ribbon cable (4 in) (d_wire = .254 mm)
	Samtec 10 pin connector ends (2 of them) (d = .4 mm)
K	4 pin Hirose connector -**IGNORE**
L	MHX 2400 Coax cable -**IGNORE**
M	**FM430 to MHX 2400 Connectors (13 pins)**
	FM430 to MHX 2400 Connectors (17 pins) close to +X side
N	**4 screws into threaded posts (13 mm) into 4 screws M2.5 x .45**
	Screws (M2.5 x .45) equiv to 3-48 screw
	Threaded posts (13 mm)
P	**Cubesat Kit bus connector (104 pin) along -X side**
P1	**Bus Connector (40 mm)**
P2	**Bus Connector (15 mm)**
P3	**Bus Connector (11.5mm)**
Q	Separation Switch connector - **IGNORE**
R	**4 M3x6 Button Socket head screws**
S	EPS to Battery Board connector (small black plastic thing) - **IGNORE**
T	3 6-pin Hirose connector - **IGNORE**
U	Unknown but guess is that its epoxy and each battery cell is soldered at 2 tabs (total of 4 tabs) - **IGNORE**
V	Beacon antenna coax cable (similar to MHX cable) -**IGNORE**
W	**4 screws (SMS Sun Sensor screws)**
X	**4 spacers**
X1	**FM430 to EPS (25 mm)**
X2	**EPS to Beacon Board (15 mm)**
X3	**Beacon Board to SMS (11.5 mm)**
X4	**SMS to midplane standoffs (spacers + standoffs + screws)**
	SMS to midplane standoff spacers (4.5 mm)
	Midplane Standoffs (5 mm) (Area ~ 8.5 x 7.0 mm)
	Chassis Screw
Y	Mini D Connector - **IGNORE**
Z	2 Mid-plane Standoffs (combo of standoffs, screw and nut) - **IGNORE**
AA	**Nufil Double Sided Kapton Tape (.002 mils Kapton, 5 mils total - assume all Kapton) PER CELL**
BB	2 Assembly Rods - **IGNORE**
CC	**Nufil Double Sided Kapton Tape (TASC cell)**
DD	**Nufil Double Sided Kapton Tape (TASC cells) ALL CELLS**
EE	**Nufil Double Sided Kapton Tape (ITJ, BTJM, Polycrystalline)**
FF	**4 Hex stud stand-offs into pressfit threaded tubes**

APPENDIX F. THERMAL RESISTANCE CALCULATIONS

Conncection	Item	Material	Source*	Thermal Conductivity (W/mk) k	Source*	Thermal Conductance (W/K) G	Source*	Electrical Resistivity (ohm-m) ρ	Source*	Electrical Conductivity (S/m) σ	Source*
A	Chassis Screws	2-56 Stainless Steel	9	16	1	0.21	2				
F	Patch Antenna Adhesive	3M 468MP (.005 mm thickness)	7	0.18	7						
G	Hex stud standoffs (tops only)	Chrome-plated brass	11	109	1			6.15E-08		1.63E+07	17
M	FM430 to MHX 2400 Connectors (2 black - 17 pins & 13 pins)	Gold Plated Phosphor Bronze	3	70	12			1.07558E-07		9.2973E+06	15
N	4 screws into threaded posts (13 mm) into 4 screws										
	Screws (M2.5 x .45) equiv to 3-48 screw	Stainless Steel	19	16	1	0.24	2				
	Threaded posts (13 mm)	Aluminum	9	167	16						
P	Cubesat Kit Bus Connector (104 Pins)	Gold Plated Phosphor Bronze	3	70	12			1.07558E-07		9.2973E+06	15
R	4 M3x6 Button Socket head screws	303/304 Stainless steel A2	20	16.2	20	0.42	2				
W	4 SMS Sun Sensor Screws	2-56 Stainless Steel	6	16	1	0.21	2				
X	4 spacers	Anodized 6061-T6 Aluminum	9	167	16			3.99E-08	16		
AA	CV silicon adhesive (double sided Kapton)	.002 mil Kapton	4	0.37	8						

Figure 56 SCAT Parts Thermal Conductivity Calculations

Sources:	
1)	http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html
2)	Thermal Control Handbook (pg 265 - table 8.4)
3)	http://www.samtec.com/ProductInformation/TechnicalSpecifications/CatalogPages.aspx?series=ESQ
4)	http://www.nusil.com/library/products/CV4-1161-5P.pdf
5)	http://www.samtec.com/ProductInformation/TechnicalSpecifications/CatalogPages.aspx?series=FFSD
6)	http://www.mcmaster.com/#91400a058/=asjcvr
7)	3M 468MP file from Mark Schreiner
8)	http://www2.dupont.com/Kapton/en_US/products/MT/index.html
9)	http://www.cubesatkit.com/
	http://www.cubesatkit.com/content/faq.html
10)	e-mail from Adam Reif at Pumpkin (1 Feb 2011)
11)	e-mail from Andrew Kalman at Pumpkin (31Jan 2011)
12)	http://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html
13)	http://www.samtec.com/documents/webfiles/pdf/FTSH_SMT.PDF
14)	http://www.ndt-ed.org/EducationResources/CommunityCollege/Materials/Physical_Chemical/Electrical.htm
	IACS : International Annealed Copper Standard
15)	http://www.copper.org/applications/industrial/designguide/conductbronze02.html
	Used avg of 16% IACS (Phosphor Bronze = 11%-20%)
16)	http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6
17)	http://www.kp44.org/ftp/ElectricalConductivityOfMaterials.php
18)	http://www.mcmaster.com/#91400a058/=aw3854
19)	http://www.mcmaster.com/#90116a112/=aw3flg
20)	Clyde Space e-mail dated 2/7/2011

			Electrical Resistance	Effective L/A	Per element							
Connection	Description	Additional Details	Re (Ω)	L/A_eff (1/m)	L (m)	A(m²)	R=L/(kA) (°C/W)	R=1/G (°C/W)	R=Re/(ρk) (°C/W)	# of elements	Rtotal (°C/W)	Units
A	1 screw (Chassis Screw)				N/A	N/A	N/A	4.761904762	N/A	1	4.7619	K/W
B	3 screws (Chassis Screw)				N/A	N/A	N/A	4.761904762	N/A	3	1.5873	K/W
C	4 clips (anodized 6061-T6 Aluminum) - IGNORE				N/A	N/A	N/A	N/A		N/A	N/A	N/A
D	Connected via the structure (1 piece of metal) - IGNORE				N/A	N/A	N/A	N/A		N/A	N/A	N/A
E	2 clips (anodized 6061-T6 Aluminum) - IGNORE				N/A	N/A	N/A	N/A		N/A	N/A	N/A
F	Built in 3M adhesive on the patch antenna				5.00E-05	7.81E-04	5.08E-02	N/A	N/A	1	0.0508	K/W
G	4 Hex stud stand-offs (tops only)	Total L = 23, Top L = 15, D = 2.5mm			0.015	1.43335E-05	9.60	N/A	N/A	4	2.4002	K/W
H	Samtec 16 pin connector + ends - IGNORE									1		K/W
	Samtec 16 pin ribbon cable (4 in) (d_wire = .254 mm)	R_contact + R_ribbon + R_contact								16		
	Samtec 16 pin connector ends (2 of them) (d= .4mm)	R_header								16		
J	Samtec 10 pin connector + ends - IGNORE											K/W
	Samtec 10 pin ribbon cable (4 in) (d_wire = .254 mm)									10		K/W
	Samtec 10 pin connector ends (2 of them) (d= .4 mm)									10		K/W
K	4 pin Hirose connector - IGNORE											
L	MHX 2400 Coax cable - IGNORE											
M	FM430 to MHX 2400 Connectors (13 pins)	L = .009 m			0.009	3.217E-07			1727.85	13	132.9115	K/W
	FM430 to MHX 2400 Connectors (17 pins) close to +X side	L = .009 m			0.009	3.217E-07			1727.85	17	101.6382	K/W
N	4 screws into threaded posts (13 mm) into 4 screws M2.5 x .45										3.6566	K/W
	Screws (M2.5 x .45) equiv to 3-48 screw							4.166666667	N/A	4		
	Threaded posts (13 mm)	L = .013 m			0.013	1.24E-05	6.29E+00			4		
P	Cubesat Kit bus connector (104 pin) along -X side	Measured	0.019	176648.32				N/A	2523.5474	104	24.2649	K/W
P1	Bus Connector (40 mm)				0.04	3.217E-07		N/A	3104.4607	104	29.8506	K/W
P2	Bus Connector (15 mm)				0.015	3.217E-07		N/A	1994.287	104	19.1758	K/W
P3	Bus Connector (11.5mm)				0.0115	3.217E-07		N/A	1838.8627	104	17.6814	K/W
Q	Separation Switch connector - IGNORE											
R	4 M3x6 Button Socket head screws				N/A	N/A	N/A	2.380952381	N/A	4	0.5952	K/W
S	EPS to Battery Board connector - IGNORE											
T	3 6-pin Hirose connector - IGNORE											
U	Unknown - battery cell is soldered at 2 tabs - IGNORE											
V	Beacon antenna coax cable (similar to MHX cable) - IGNORE											
W	4 screws (SMS Sun Sensor screws)				N/A	N/A	N/A	4.761904762	N/A	4	1.1905	K/W
X	4 spacers											
X1	FM430 to EPS (25 mm)				0.025	6.65232E-06	22.50350912			4	5.6259	K/W
X2	EPS to Beacon Board (15 mm)				0.015	6.65232E-06	13.50210547			4	3.3755	K/W
X3	Beacon Board to SMS (11.5 mm)				0.0115	6.65232E-06	10.3516142	N/A	N/A	4	2.5879	K/W
X4	SMS to midplane standoffs (spacers + standoffs + screws)									2	4.6579	K/W
	SMS to midplane standoff spacers (4.5 mm)				0.0045	6.65232E-06	4.050631642			1	4.0506	K/W
	Midplane Standoffs (5 mm) (Area ~ 8.5 x 7.0 mm)				0.005	0.0000595	0.50319529			1	0.5032	K/W
	Chassis Screw							4.761904762		1	4.7619	K/W
Y	Mini D Connector - IGNORE											
Z	2 Mid-plane Standoffs - IGNORE											
AA	Nufil Double Sided Kapton Tape (assume all Kapton) PER CELL	.002 mils Kapton, 5 mils total			0.000127	0.002672	0.183513282	N/A	N/A	1	0.1835	
BB	2 Assembly Rods - IGNORE											
CC	Nufil Double Sided Kapton Tape (TASC cell)				0.000127	0.0002457	1.995716281	N/A	N/A	1	1.9957	
DD	Nufil Double Sided Kapton Tape (TASC cells) ALL CELLS				0.000127	0.0019656	0.249464535	N/A	N/A	1	0.2495	
EE	Nufil Double Sided Kapton Tape (ITJ, BTJM, Polycrystalline)				0.000127	0.0013466	0.36413745	N/A	N/A	1	0.3641	
FF	4 Hex stud stand-offs into pressfit threaded tubes				N/A	N/A	N/A	4.761904762	N/A	4	1.1905	K/W

Figure 57 SCAT Thermal Resistance Calculations

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APPENDIX G. TVAC TEMPERATURE PROFILE

Table 19 TVAC Temperature Profile

Time (secs)	Temp (˚ C)
0	20.6
600	20.5
1200	19.1
1800	18.1
2400	16.6
3000	26.2
3600	26.8
4200	31.8
4800	46.5
5400	46.1
6000	47.4
6600	46.4
7200	47.2
7800	48.5
8400	47.5
9000	36.5
9600	21.9
10200	13.4
10800	8.3
11400	5.2
12000	3.3
12600	-1.3
13200	-0.2
13800	-1.6
14400	-6.7
15000	-9.9
15600	-14.2
16200	-27.6
16800	-38.7
17400	-42.6
18000	-47
18600	-54.4
19200	-71.5
19800	-100
20400	-100
21000	-100
21600	-100
22200	-100
22800	-100
23400	-100
24000	-100
24600	-100.1
25200	-100
25800	-57.6
26400	-26.8

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